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From Benchmarking Resilience to Accelerating Transformation Using Crowdsourcing Data

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Preface

This thesis is submitted in partial fulfillment of the requirements for obtaining the Ph.D. degree in Urban Planning and Land Management Group, Institute of Geodesy and Geoinformation at the University of Bonn. The thesis follows a paper-based approach in accordance with the guidelines of the University of Bonn. List of publications appended to this thesis includes:

1. M. Moghadas, A. Asadzadeh, A. Vafeidis, A. Fekete, T. Kötter, A multi-criteria approach for assessing urban flood resilience in Tehran, Iran, Int. J. Disaster Risk Reduct. 35 (2019) 101069. https://doi.org/10.1016/j.ijdrr.2019.101069.
2. M. Moghadas, A. Rajabifard, A. Fekete, T. Kötter, A Framework for Scaling Urban Transformative Resilience through Utilizing Volunteered Geographic Information, ISPRS Int. J. Geo-Information. 22 (2022) 114. https://doi.org/https://doi.org/10.3390/ijgi11020114.
3. M. Moghadas, A.Fekete, A. Rajabifard, T. Kötter, The wisdom of crowds for disaster resilience: A near-real-time analysis of social media data on the July 2021 flood in Germany, Under review of Geojournal (GEJO-D-22-01434R1).

Contributions of co-authors to the above publications: Supervision, consulting for conception, critical review of articles, and final approval of versions to be published. All co-authors agreed on the inclusion of these manuscripts in this thesis.

The following papers, conference abstracts, and conference papers were also written during the Ph.D. period, and deal with the general topic of the thesis:

4. A. Asadzadeh, T. Koetter, A. Fekete, **M. Moghadas**, M. Alizadeh, E. Zebardast, D. Weiss, M. Basirat, Urbanization, migration, and the challenges of resilience thinking in urban planning : Insights from two contrasting planning systems in Germany and Iran, Cities. 125 (2022) 103642. https://doi.org/10.1016/j.cities.2022.103642.
5. A. Fekete, A. Asadzadeh, M. Ghafory-Ashtiany, K. Amini-Hosseini, C. Hetkämper, **M. Moghadas**, A. Ostadtaghizadeh, A. Rohr, T. Kötter, Pathways for advancing integrative disaster risk and resilience management in Iran:

Needs, challenges and opportunities, Int. J. Disaster Risk Reduct. 49 (2020). https://doi.org/10.1016/j.ijdrr.2020.101635.

6. **Moghadas, M.** , Fekete, A., Asadzadeh, A., Kötter, T. (2018) A theoretical framework for building the risk-resilience of basic infrastructures and services using Open Data, abstract published in 11th International Forum on Urbanism (IFoU) Congress, Reframing Urban Resilience Implementation: Aligning Sustainability and Resilience, December 10-11-12, Barcelona, Spain.

7. **Moghadas, M.,** Fekete, A., Asadzadeh, A., Kötter, T. (2018) Measuring urban disaster resilience: The context of flood hazard in the city of Tehran, published in EGU General Assembly, Geophysical Research AbstractsVol. 20, EGU2018-148-2, April 2018, Vienna, Austria.

8. Asadzadeh, A., **Moghadas. M.** Koetter. T. Fekete. A. (2018) Bridging the gap between stakeholder requirements and technical needs in community resilience measurement, abstract published in 11th International Forum on Urbanism (IFoU) Congress, Reframing Urban Resilience Implementation: Aligning Sustainability and Resilience, December 10-11-12, Barcelona, Spain.

Summary

Resilience to disasters in times of climate change underscores the importance of reflexive governance, facilitation of socio-technical co-evolution, inclusive co-creation of knowledge, and innovative and collaborative learning processes. In the face of climate change, reactive and backward-looking disasters and risk management will not be able to address the coming threats. Natural disasters are expected to increase in frequency and magnitude. This requires prevention, anticipation, and early warning at the local and global levels, as well as building absorption, adaptation, and transformation capacities. The problem for local communities is not only the increase but also the exposure to new and unknown hazards. Therefore, reducing risk and increasing resilience are important and central goals of global development agendas, namely the Sendai Framework, the Paris Agreement, the Sustainable Development Goals, and the New Urban Agenda. In addition, academic circles have highlighted the importance of building urban resilience by considering the important role of governance, people, and technology in addressing challenges and creating solutions in a place-based, integrated, inclusive, systemic, risk-aware, and forward-looking manner.

Thus, the overall goal of this thesis is to develop, test, and improve methods for assessing and strengthening resilience to climate change through new methods and data innovations bridging nomothetic/top-down to idiographic/bottom-up approaches. To achieve this goal, three main contributions were made:

Operationalizing the concept of urban resilience to flooding, developing a resilience index, and cross-validating empirical results are important milestones toward a better understanding of both the characteristics that contribute to urban resilience to climate-related hazards and the interactions required to build and sustain it. While static measurement of inherent urban resilience and baseline condition has received much attention recently, there has been no optimal approach to operationalizing this concept. Thus, there is a need for more empirical studies of what constitutes disaster resilience and how it can be assessed. To this end, disaster resilience measurement frameworks were analyzed and the Baseline Resilience Indicators for Community (BRIC) framework was adopted as the most widely used framework as a sound theoretical basis for developing primary resilience indicators for the city of Tehran in Iran. A comprehensive wish list of solid, robust, and sound resilience indicators was compiled from the literature. Multivariate assessments were conducted for data reduction and factor retention. Indicators were then weighted by experts, including academics and practitioners, and aggregated by the hybrid method of multicriteria decision-making (MCDM) using the analytic hierarchy process and the technique of order preference by similarity to an ideal solution (AHP-TOPSIS). The

composite indicator approach is based on secondary data and its limitations in measuring resilience to flooding are well known. In particular, the softer and qualitative factors of resilience, while no less important, are not yet adequately captured by secondary data. For monitoring, real-time situational awareness, and data-driven analysis municipalities lack the resources in terms of labor and knowledge to regularly collect qualitative data that capture the emerging dynamic disaster-related patterns in communities. Given technological-social co-evolution and digital transformation, the use of new data sources such as crowdsourcing and Volunteered Geographic Information (VGI) and crowdsourcing can partially fill this disaster-related data gap.

A framework for scaling transformative urban resilience through the use of VGI was therefore developed to provide a comprehensive understanding of the complexity and capacity of using VGI for transformative disaster resilience, which was identified as a research gap. The need to move toward a sustainable future and bounce forward after any disruption has led recent urban resilience initiatives to embrace the concept of transformative resilience when and where conventional and top-down resilience initiatives are less likely to deliver effective strategies, plans, and actions. Transformative resilience pathways emphasize the importance of reflexive governance, inclusive co-creation of knowledge, innovative and collaborative learning, and self-organizing processes. To support these transformative pathways, VGI and crowdsourcing data can overcome the challenges associated with authoritative data that are bound by administrative boundaries and do not cover qualitative factors. Crowdsourcing and VGI-based models can be considered either as stand-alone or complementary mechanisms when and where conventional approaches are less suited to promote collective community resilience and institutional collaboration, and administrative datasets are less suited to provide open, accessible, and timely geospatial information to both the community and decision-makers. Based on a qualitative content analysis of available resources, the second contribution explores key aspects of using VGI for transformative disaster resilience and proposes a comprehensive framework structured around 18 key concepts under five identified legal, institutional, social, economic, and technical aspects to formalize the process of adopting VGI in transformative resilience initiatives. The synthesis framework could be considered a guide for researchers and practitioners on how to use VGI in disaster resilience initiatives, taking into account a comprehensive understanding of the complexities and interrelationships of legal, institutional, technical, and socioeconomic aspects within each jurisdiction. Indeed, a shared understanding of the benefits of emerging trends in geospatial data, smart technologies, and spatial analytics using new data and tools can bring governments, industry, and communities together to effectively build sustainable and resilient communities. In applying this framework, legal (e.g., open standards for open source and user-generated geospatial data), socioeconomic (e.g., digital divide, marginalization of certain groups, and ethical issues), and technical (e.g., data maintenance, intrinsic and extrinsic data quality) challenges or barriers should be analyzed accordingly to prevent the emergence of new risks. In the next paper, therefore, the proposed framework is partially applied to assess how such an initiative can contribute to better disaster situational awareness and evidence-based decision-making.

A near-real-time analysis of social media data and an online survey on the July 2021 flood in Germany to leverage collective sensing approaches to increase evidence-based resilience to an unforeseen event was conducted as the third contribution. Emerging dynamic patterns within communities should be captured to expand the boundaries of approaches to resilience measurement that use a predefined list of indicators, including environmental, social, economic, institutional, and infrastructural variables. This understanding contributes to the urgent need to move from a reactive to a proactive approach to natural hazard management, with dynamic and data-driven monitoring and assessment of climate resilience over time and space. Digital transformation also enables the use of Big Data derived from crowdsourcing, social media, and Volunteered Geographic Information (VGI), and its analysis through large-scale observations and social sensing techniques. This study aimed to code social media messages (public attitudes) into different topics within disaster phases in near real-time by examining German Twitter data when the flood disaster hit Germany in July 2021 in parallel with the coronavirus pandemic. In addition to semantic (textual) analysis, spatiotemporal patterns of online disaster communication are also assessed. As an additional data layer, an online survey of responders (key stakeholder groups) involved in the flood response was conducted with open-ended questions to determine their perceptions of issues and capacities. To extract latent topics from the corpora of both data layers, Latent Dirichlet Allocation (LDA) was used as an unsupervised Machine Learning approach. Based on the knowledge domain, the extracted topics discussed online were then compiled into five themes related to disaster resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) to reflect people's and stakeholders' perceptions and expectations for improved disaster resilience. This collective, real-time approach can provide valuable information ranging from early identification of needed actions to insights for developing resilience strategies to increase resilience to unforeseen disasters in an evidence-based manner.

Kurzfassung

Die Widerstandsfähigkeit gegenüber Katastrophen in Zeiten des Klimawandels unterstreicht die Bedeutung einer reflexiven Governance, der Erleichterung der sozio-technischen Ko-Evolution, der inklusiven Ko-Kreation von Wissen und innovativer und kollaborativer Lernprozesse. Angesichts des Klimawandels wird ein reaktives und rückwärtsgewandtes Katastrophen- und Risikomanagement nicht in der Lage sein, die kommenden Bedrohungen zu bewältigen. Die Häufigkeit und das Ausmaß von Naturkatastrophen werden voraussichtlich zunehmen. Dies erfordert Prävention, Antizipation und Frühwarnung auf lokaler und globaler Ebene sowie den Aufbau von Absorptions-, Anpassungs- und Transformationskapazitäten. Das Problem für lokale Gemeinschaften besteht nicht nur in der Zunahme, sondern auch in der Exposition gegenüber neuen und unbekannten Gefahren. Daher sind die Verringerung des Risikos und die Erhöhung der Widerstandsfähigkeit wichtige und zentrale Ziele der globalen Entwicklungsagenden, insbesondere des Sendai-Rahmens, des Pariser Abkommens, der Ziele für nachhaltige Entwicklung und der New Urban Agenda. Darüber hinaus haben akademische Kreise die Bedeutung des Aufbaus städtischer Resilienz hervorgehoben, indem sie die wichtige Rolle von Governance, Menschen und Technologie bei der Bewältigung von Herausforderungen und der Schaffung von Lösungen in einer ortsbezogenen, integrierten, inklusiven, systemischen, risikobewussten und vorausschauenden Weise berücksichtigt haben.

Das übergeordnete Ziel dieser Arbeit ist daher die Entwicklung, Erprobung und Verbesserung von Methoden zur Bewertung und Verbesserung der Resilienz gegenüber dem Klimawandel. Um dieses Ziel zu erreichen, wurden drei Hauptbeiträge geleistet:

Die Operationalisierung des Konzepts der städtischen Resilienz gegenüber Überschwemmungen, die Entwicklung eines Resilienzindexes und die Kreuzvalidierung der empirischen Ergebnisse sind wichtige Meilensteine auf dem Weg zu einem besseren Verständnis sowohl der Merkmale, die zur städtischen Resilienz gegenüber klimabedingten Gefahren beitragen, als auch der Wechselwirkungen, die für den Aufbau und die Aufrechterhaltung dieser Resilienz erforderlich sind. Während die statische Messung der inhärenten Widerstandsfähigkeit von Gemeinden und des Ausgangszustands in letzter Zeit viel Aufmerksamkeit erhalten hat, gab es bisher keinen optimalen Ansatz zur Operationalisierung dieses Konzepts. Es besteht daher ein Bedarf an mehr empirischen Studien darüber, was Katastrophenresilienz ausmacht und wie sie bewertet werden kann. Zu diesem Zweck wurden die Rahmenwerke zur Messung der Katastrophenresilienz analysiert und das Rahmenwerk "Baseline Resilience Indicators for Community" (BRIC) als das am häufigsten verwendete Rahmenwerk als solide theoretische Grundlage für die

Entwicklung primärer Resilienzindikatoren für die Stadt Teheran im Iran angenommen. Aus der Literatur wurde eine umfassende Wunschliste von soliden, robusten und fundierten Resilienzindikatoren zusammengestellt. Für die Datenreduktion und die Beibehaltung der Faktoren wurden multivariate Bewertungen durchgeführt. Die Indikatoren wurden dann von Experten, darunter Akademiker und Praktiker, gewichtet und mit der hybriden Methode der multikriteriellen Entscheidungsfindung (MCDM) unter Verwendung des analytischen Hierarchieprozesses und der Technik der Ordnungspräferenz durch Ähnlichkeit mit einer idealen Lösung (AHP-TOPSIS) zusammengefasst. Der Ansatz der zusammengesetzten Indikatoren basiert auf Sekundärdaten, und seine Grenzen bei der Messung der Widerstandsfähigkeit gegenüber Überschwemmungen sind bekannt. Insbesondere die weicheren und qualitativen Faktoren der Widerstandsfähigkeit, die zwar nicht weniger wichtig sind, werden durch Sekundärdaten noch nicht angemessen erfasst. Für die Überwachung, das Echtzeit-Situationsbewusstsein und die datengestützte Analyse fehlen den Kommunen die Ressourcen in Form von Arbeit und Wissen, um regelmäßig qualitative Daten zu erheben, die die entstehenden dynamischen katastrophenbezogenen Muster in den Gemeinden erfassen. Angesichts der technologisch-sozialen Koevolution und der digitalen Transformation kann die Nutzung neuer Datenquellen wie Crowdsourcing und Volunteered Geographic Information (VGI) und Crowdsourcing diese katastrophenbezogene Datenlücke teilweise schließen.

Daher wurde ein **Rahmen für die Skalierung der transformativen urbanen Resilienz durch den Einsatz von VGI** entwickelt, um ein umfassendes Verständnis für die Komplexität und Kapazität des Einsatzes von VGI für die transformative Katastrophenresilienz zu schaffen, die als Forschungslücke identifiziert wurde. Die Notwendigkeit, sich auf eine nachhaltige Zukunft zuzubewegen und nach jeder Störung wieder auf die Beine zu kommen, hat dazu geführt, dass neuere städtische Resilienzinitiativen das Konzept der transformativen Resilienz aufgreifen, wenn und wo konventionelle und von oben nach unten gerichtete Resilienzinitiativen wahrscheinlich keine wirksamen Strategien, Pläne und Maßnahmen liefern. Transformative Resilienzpfade betonen die Bedeutung von reflexiver Governance, inklusiver Ko-Kreation von Wissen, innovativem und kollaborativem Lernen und selbstorganisierenden Prozessen. Um diese transformativen Wege zu unterstützen, können VGI- und Crowdsourcing-Daten die Herausforderungen überwinden, die mit autoritativen Daten verbunden sind, die an administrative Grenzen gebunden sind und keine qualitativen Faktoren abdecken. Crowdsourcing- und VGI-basierte Modelle können entweder als eigenständige oder ergänzende Mechanismen in Betracht gezogen werden, wenn und wo konventionelle Ansätze weniger geeignet sind, um die kollektive Widerstandsfähigkeit der Gemeinschaft und die institutionelle Zusammenarbeit zu fördern, und administrative Datensätze weniger geeignet sind, um offene, zugängliche und zeitnahe Geoinformationen sowohl für die Gemeinschaft als auch für Entscheidungsträger bereitzustellen. Auf der Grundlage einer qualitativen Inhaltsanalyse verfügbarer Ressourcen untersucht der zweite Beitrag die Schlüsselaspekte der Nutzung von VGI für eine transformative Katastrophenresilienz und schlägt einen umfassenden Rahmen vor, der um 18 Schlüsselkonzepte unter fünf identifizierten rechtlichen, institutionellen, sozialen, wirtschaftlichen und technischen Aspekten strukturiert ist, um den Prozess der Übernahme von VGI in transformative Resilienzinitiativen zu formalisieren. Der zusammenfassende Rahmen könnte als Leitfaden für Forscher und Praktiker betrachtet werden, wie VGI in Initiativen zur Katastrophenresilienz eingesetzt werden können, wobei ein umfassendes Verständnis der Komplexität und der Wechselbeziehungen zwischen rechtlichen, institutionellen, technischen und sozioökonomischen Aspekten innerhalb der jeweiligen Rechtsprechung berücksichtigt wird. In der Tat kann ein gemeinsames Verständnis der Vorteile aufkommender Trends bei Geodaten, intelligenten Technologien und räumlichen Analysen unter Verwendung neuer Daten und Werkzeuge Regierungen, Industrie und Gemeinschaften zusammenbringen, um nachhaltige und widerstandsfähige Gemeinschaften effektiv aufzubauen. Bei der Anwendung dieses Rahmens sollten rechtliche (z. B. offene Standards für Open-Source- und nutzergenerierte Geodaten), sozioökonomische (z. B. digitale Kluft, Marginalisierung bestimmter Gruppen und ethische Fragen) und technische (z. B. Datenpflege, intrinsische und extrinsische Datenqualität) Herausforderungen oder Hindernisse entsprechend analysiert werden, um das Entstehen neuer Risiken zu verhindern. Im nächsten Beitrag wird daher der vorgeschlagene Rahmen teilweise angewandt, um zu bewerten, wie eine solche Initiative zu einem besseren Situationsbewusstsein bei Katastrophen und einer evidenzbasierten Entscheidungsfindung beitragen kann.

Als dritter Beitrag wurde eine **Fast-Echtzeit-Analyse von Social-Media-Daten und eine Online-Umfrage zum Juli-Hochwasser 2021 in Deutschland** durchgeführt, um kollektive Sensing-Ansätze zu nutzen, um die evidenzbasierte Resilienz gegenüber einem unvorhergesehenen Ereignis zu erhöhen. Aufkommende dynamische Muster innerhalb von Gemeinschaften sollten erfasst werden, um die Grenzen von Ansätzen zur Resilienzmessung zu erweitern, die eine vordefinierte Liste von Indikatoren verwenden, einschließlich ökologischer, sozialer, wirtschaftlicher, institutioneller und infrastruktureller Variablen. Dieses Verständnis trägt zur dringenden Notwendigkeit bei, von einem reaktiven zu einem proaktiven Ansatz für das Management von Naturgefahren überzugehen, mit dynamischer und datengesteuerter Überwachung und Bewertung der Klimaresilienz über Zeit und Raum. Die digitale Transformation ermöglicht auch die Nutzung von Big Data, die aus Crowdsourcing, sozialen Medien und freiwilligen geografischen Informationen (Volunteered Geographic Information, VGI) stammen, sowie deren Analyse durch groß angelegte Beobachtungen und

Social-Sensing-Techniken. Diese Studie zielte darauf ab, Social-Media-Botschaften (öffentliche Einstellungen) zu verschiedenen Themen innerhalb von Katastrophenphasen in nahezu Echtzeit zu kodieren, indem deutsche Twitter-Daten untersucht wurden, als Deutschland im Juli 2021 von der Hochwasserkatastrophe parallel zur Coronavirus-Pandemie heimgesucht wurde. Neben der semantischen (textuellen) Analyse werden auch raum-zeitliche Muster der Online-Katastrophenkommunikation untersucht. Als zusätzliche Datenschicht wurde eine Online-Befragung der an der Flutkatastrophe beteiligten Akteure (Schlüsselakteure) mit offenen Fragen durchgeführt, um ihre Wahrnehmung von Problemen und Kapazitäten zu ermitteln. Um latente Themen aus den Korpora beider Datenschichten zu extrahieren, wurde Latent Dirichlet Allocation (LDA) als unüberwachter maschineller Lernansatz verwendet. Auf der Grundlage der Wissensdomäne wurden die extrahierten Themen, die online diskutiert wurden, dann zu fünf Themen im Zusammenhang mit der Katastrophenresilienz (präventiv, antizipativ, absorptiv, adaptiv und transformativ) zusammengestellt, um die Wahrnehmungen und Erwartungen der Menschen und Interessengruppen für eine verbesserte Katastrophenresilienz widerzuspiegeln. Dieser kollektive Echtzeit-Ansatz kann wertvolle Informationen liefern, die von der frühzeitigen Identifizierung notwendiger Maßnahmen bis hin zu Erkenntnissen für die Entwicklung von Resilienzstrategien reichen, um die Widerstandsfähigkeit gegenüber unvorhergesehenen Katastrophen auf evidenzbasierte Weise zu erhöhen.

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CHAPTER 1

INTRODUCTION

CHAPTER 1: INTRODUCTION

1. Motivation and research gap

Climate change is internationally recognized as a phenomenon that poses serious threats and risks across regions, sectors, and communities. The recently released 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) warns that extreme events such as floods, droughts, and heat waves will continue to increase in both frequency and severity in the coming decades [1]. Climate change has far-reaching implications for both the global South and the global North as it threatens human and ecological systems. Therefore, the collective resilience of communities to unforeseen disasters and shocks should be strengthened and their vulnerability to climate-related extreme events reduced in various jurisdictions [2,3]. From the growing spectrum of risks stemming from climate change, more frequent and severe floodings both in developed and less developed countries are reported [4] and since cities are at the forefront of increasing flood-related loss and damages, flood resilience has to be part of sustainable urban development and climate resilience plans [2,3,5].

In the field of natural hazards, resilience has become increasingly important and is documented by an exponential increase in the literature. To understand how the term is used and applied in the scientific community, Meerow analyzed 57 definitions of resilience and defined urban resilience as “the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales- to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change and to quickly transform systems that limit current or future adaptive capacity” [6]. However, since urban resilience is a complex and difficult concept to operationalize, developing a sound technique or method to realize the concept would be an important milestone in understanding the factors and interactions that contribute to, build, and enhancing resilience [7–13]. Indeed, there is no optimal approach to operationalizing this concept so far. Therefore, more empirical studies need to be conducted on what constitutes disaster resilience and how to assess it.

Furthermore, after measuring the resilience baseline condition, for improving disaster resilience as a dynamic process, the development of strategies based on the open exchange and collaboration at multiple levels (top-down and bottom-up approaches) should be considered, and the use of digital technologies and data innovations such as Big Data and citizen-generated data should be promoted [14,15]. Therefore, in the era of digital and data transformation, countries should explore the added value of using other data such as social media crowdsourcing and Volunteered Geographic Information (VGI) to improve data capabilities leading to timely access to geospatial data, evidence-based decision-making, improving the applicability of disaster-related data, overcoming institutional barriers in time-sensitive situations, and strengthening community resilience by connecting people to geospatial services [14,16–19]. However, there is no comprehensive overview of the aspects that might influence the use of crowdsourcing in disaster resilience initiatives, nor of the application of crowdsourcing and VGI data that can be leveraged for improved bottom-up disaster resilience.

Thus, the overarching goal of this thesis is to develop, test, and improve methods for assessing and strengthening community resilience as a multi-faceted phenomenon to flooding through new approaches and using new data.

2. Research background

2.1 Community disaster resilience

Disaster resilience is a concept that has gained increasing attention over the past two decades and aims to reduce the negative impacts of natural, man-made, and climatic hazards. Resilience has become an important goal for cities and communities, especially in the face of climate change and the associated environmental, socioeconomic, and political risks and uncertainties [6]. While the term resilience has received attention from different scientific communities over time, finding an agreement upon a standard definition of resilience in the literature is challenging [6,9,20–24]. But in the realm of urban and community resilience, the three definitions for resilience and urban resilience and resilience capacities were adapted for this thesis:

Cutter et al. [25] define resilience as "the ability of a social system to respond and recover from disasters and the inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event adaptive processes that facilitate the ability of the social system to re-organize, change, and learn in response to a threat". Meerow et al. [26] define urban resilience as "the ability of an urban system- and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales- to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change and to quickly transform systems that limit current or future adaptive capacity".

Manyena et al. [27] present five inductive resilience capacities as preventive, anticipative, absorptive, adaptive, and transformative capacities. *Preventive capacity* is the ability of systems to adopt sustainable pathways and reduce the vulnerability, presence, or impact of hazards; *anticipative capacity* is the ability to understand risks based on risk data and scenarios to predict where, when, and whom disaster will affect;

absorptive capacity is the ability of systems to withstand change and bounce back to a previous state; *adaptive capacity refers to* adjustment to change and reorganizing without major qualitative changes in functions or structures; and *transformative capacity* implies transformation through learning, self-organization, and exploration of new pathways along with flexibility and significant changes to existing structures [13,25,27–33].

Indeed, urban resilience is a complex concept and difficult to be measured and operationalized. A variety of frameworks and approaches are developed to operationalize urban resilience at different geographical scales and hazard contexts [9,33,34]. The frameworks define resilience in a slightly different way. However, most of them use a hierarchical structure and define main dimensions or components, which are addressed by associated indicators. In Table 1 the most applied and well-known resilience frameworks along with their components, scale of analysis, and hazard context are shown.

Table 1: Resilience frameworks; adapted from [8,26]

Resilience Framework	Authors	Components	Scale/Unit of analysis	Hazard Context
BRIC Baseline Resilience Indicators for Communities	Cutter et al. [23,35,36]	Social, Community Capital, Economic, Technical, Institutional, Environmental	community/ county	Multiple hazards (flood)
RCI Resilience Capacity Index	Foster et al [37]	Economic, Socio-demographic, and Community connectivity capacities	Region/ metropolitan area	Multiple hazards
PEOPLES Resilience Framework	Renschler et al. [38]	Population & demographics, Environmental/ecosystem, Services, Infrastructure, Lifestyle, Economic, Social-cultural resilience	Community /county	Multiple hazards (earthquake)
CRF City Resilience Framework	Arup & The Rockefeller Foundation [39]	Socio-ecological Resilience: Ecosystem, Infrastructure, Institutions, Knowledge, Social agents	City/Urban systems	Multiple hazards
UCR Urban Climate Resilience	Tyler and Moench [11]	Urban systems, Agents (people and organizations), and Institutions	City/Urban systems	Multiple hazards (climatic)
DRI Disaster Resilience Index	Khazai et al. [33]	Legal and institutional, awareness and capacity building, critical infrastructure	Multiple scales	Multiple hazards (earthquake)

		resilience, emergency preparedness, response and recovery planning, development planning, and risk mitigation		
UNISDR Disaster resilience scorecard for cities	UNISDR [40]	Institutional, Financial, Natural, Infrastructural, Societal, and Cultural Resilience	City/Urban systems	Multiple hazards
DRIFT Disaster Resilience Integrated Framework for Transformation	Manyena et al. [27]	Preventive, Anticipative, Absorptive, Adaptive, and Transformative capacities	Multiple scales	Multiple hazards

In addition, the construction of a composite indicator to benchmark the concept of resilience as a multifaceted phenomenon has received considerable attention [7,31,36,41–47]. A composite indicator "aggregates multiple individual indicators to provide a synthetic measurement of a complex, multidimensional, and meaningful phenomena" [12]. This approach assesses and compares the level of resilience within specific communities for any geographic area [35,48]. Although Cutter et al [36] analyzed the frequency with which certain indicators were used in different studies to identify the most commonly used indicators, there is no universally accepted set of indicators for measuring resilience. An important aspect of climate resilience is community capital and social dimensions (e.g., community support, and sense of belonging), which are rarely adequately addressed due to the lack of data on such soft elements. Since it is difficult to find a standard procedure for developing composite indicators due to the diversity of theoretical underpinnings, the majority of the relevant literature emphasizes the need for a flexible and transparent process and place-based models for a fuller understanding of measuring resilience [7,12,23,34,49–52].

2.2 VGI and crowdsourcing social media

As promoted in international development agendas, measures and mechanisms need to be developed based on open and near real-time access to spatial and risk-related information that enables better and more rapid communication, knowledge sharing, and collaboration in decision-making processes across scales, actors, and people to foster synergies and minimize conflict to improve the overall resilience of communities to disasters [2,3,5,14]. Moreover, facilitates the use of Big Data derived from sources like as crowdsourcing, social media, and VGI, as well as its analysis using social sensing techniques. Profound changes in geospatial technologies such as Digital Twins, Web 2.0, advances in 5G, and new data sources such as mobile communications, Big Data, volunteer crowdsourcing, digital volunteering, and geotagging derived urban resilience processes to rethink some of the core concepts and methods they have relied on and to effectively leverage technological capabilities to proactively transform disaster management, planning, and practices [15,16,53–56]. Specifically, data-driven transformation pathways are the generation, use, and sharing of geospatial data openly and efficiently with advanced tools, as well as better urban analytics and simulations that lead to improved decision-making capabilities based on near real-time information, reduced disaster impacts, and improved community resilience in the short, medium, and long term [15,57–59].

The term crowdsourcing describes data collection and dissemination by large and diverse groups of people who use web technology (user-generated content) but may not be trained surveyors or have specialized computer skills [60]. It has also been more than a decade since Goodchild [54] defined VGI as "the harnessing of tools to create, assemble, and disseminate geographic data provided voluntarily by individuals". Since then, VGI activities ranging from contributions to online crowdsourced mapping to location-related posts on social media contributions have transformed the process of acquiring or providing geospatial data, largely influencing traditional authoritative systems and creating new forms of public engagement based on voluntary contributions [53,61–64].

To obtain better location-based information, online social networks such as Twitter, Facebook, and Instagram, as some sources of crowdsourcing data, provide a unique platform in an online space through which collective place-based knowledge, experiences, and wisdom of a community can be captured, shared, exchanged, or discussed using the Internet or mobile phone [65]. These communication channels are particularly useful for situational awareness, distributed problem-solving, and collective action especially during disasters [66]. The development of online social networks as new forms of communication has also increased their value to researchers interested in gaining insights about or from individuals and communities to embed local and contextual knowledge as collective intelligence for collective resilience [67].

In this context, crowdsourcing, VGI, and social media data offer alternatives and complementary opportunities to collect, share and use geospatial data across different geographic and administrative scales that are otherwise extremely difficult and costly to collect [68]. Moreover, it supports the provision of near real-time, affordable, up-to-date, flexible, and fit-for-purpose geospatial information to extend the limits of conventional geospatial data infrastructures [54,69]. Social media and crowdsourcing also enable the participation of citizens who are not otherwise involved in scientific or administrative activities. Leveraging these new data sources and applying cutting-edge methods and technologies such as Machine Learning (ML), artificial intelligence (AI), or digital twins enable service diversification and innovative processes by creating alternatives based on a system-wide or cross-system perspective, leading to better urban analytics and informed decision making to improve resilience. [16,58,70].

2.3 VGI and crowdsourcing social media in disaster resilience

After gaining a fuller understanding of how to measure the unmeasurable and benchmarking the disaster resilience concept, it is necessary to improve the resilience levels of communities. A greater emphasis on disaster resilience building requires a shift in focus from a command-and-control model to a more strategic, participatory, and dialogic model by promoting new and innovative technical and scientific methods through community and stakeholder collaboration processes [13,71]. In the era of digital transformation, countries explore the added value of using user-generated content, such as social media data and VGI to improve their data capabilities in information gathering and collaboration for crisis management [17].

Moreover, Haklay [72] highlights that the level of participation in citizen science projects has four levels, in which crowdsourcing (people as sensors and volunteered computing) is the first level, and distributed intelligence (people as basic interpreters and volunteered thinking) is the second level of participation. Therefore, participatory sensing approaches like “People as Sensors”, and Collective Sensing [73] can undoubtedly play a key role in better disaster resilience planning.

The “wisdom of crowds” has been investigated in psychology already before the advent of modern social media [74]. The collaborative nature of social media crowdsourcing enables crowds of people with diverse knowledge to create, share, and exchange new opinions, experiences, and potential solutions to intractable problems and challenges leveraging the collective intelligence of the crowd [75]. Since disaster resilience relies on collaboration, people-centric approaches, and innovative strategies, the impact of gathering and sharing knowledge with a larger group of individuals allows for novel ways of disaster risk management, such as multilateral communication, real-time situational awareness, and redundancy in the early warning system, supporting self-organized peer-to-peer help activities and also cooperate on to detect, classify, and correct rumors [59,75,76].

VGI attributes such as its timeliness-reflecting spatial dynamics [77], facilitating multidirectional communication, increasing situational awareness, and enabling collective intelligence may outperform traditional geospatial datasets [61,78]. The development of online social networks for personal communication has also increased their value to researchers interested in gaining fundamental insights about individuals and communities (collective intelligence and collective action) from these user-generated data that leverage specific local and contextual knowledge [67].

Thus, utilizing social media data and VGI in disaster resilience initiatives can not only help fill the gap in disaster-related geospatial data by engaging volunteers to co-create, curate, and disseminate free, up-to-date, and near-real-time geospatial information [61,79,80], but also create an opportunity for self-organization within the digital volunteer network and enabling remote citizens and volunteers to effectively and actively contribute to disaster resilience initiatives using their technical, local, and on-site knowledge [81–83]. Moreover, the use of such collaborative data ecosystems plays an important role in improving the accessibility of geospatial information and techno-social tools for all and opens opportunities for developing innovative customized tools that contribute to disaster risk reduction and community resilience [16,84]. Previous studies have discussed the opportunities and challenges associated with using VGI for disaster resilience, but they have lacked conceptual framework underpinnings, and thus, the overall picture of VGI for urban resilience remained unclear. Therefore, various aspects of using VGI to facilitate and support disaster resilience should be addressed.

Furthermore, many studies examined crowdsourcing data obtained from social media platforms, particularly Twitter Open Application Programming Interface (API), for disaster response and coordination [85–89]. However, there is a lack of empirical research on the role of the sense of community in social media crowdsourcing during disasters that utilize and code VGI-driven data to reflect people's perceptions and expectations for improved disaster resilience as a bottom-up approach. Therefore, this gap should empirically be addressed by leveraging a collective real-time sensing approach that can provide valuable information ranging from early identification of needed actions to insights for developing resilience strategies to increase evidence-based resilience to unforeseen disasters.

3. Research problem

Climate resilience has become an increasingly important issue at all spatial scales, from the local to the global, due to more frequent and severe climate change-induced disasters such as flooding. Therefore, more empirical studies are needed that aim to develop resilience models for benchmarking flood resilience, as well as proactive and bottom-up approaches for collective resilience improvement. However, the interdisciplinary and cross-scale nature of flood resilience makes its measurement and benchmarking complex. Therefore, a transparent approach to measuring static conditions and operationalizing the concept of flood resilience from a top-down perspective is needed for the development of a flood resilience index. Furthermore, flood resilience, combined with the importance of soft and qualitative attributes, presents a significant challenge in capturing the dynamic process of transitioning from inherent pre-event resilience to post-event resilience. Although crowdsourcing and VGI-based approaches are potential bottom-up approaches to overcome this problem, little is known about how and with what considerations these new data sources (VGI and social media crowdsourcing) can help onsiderations these new data sources (VGI and social media crowdsourcing) can help improve collective resilience through bottom-up processing based on incoming primary data from communities to capture dynamic processes and capacity indicators to improve evidence-based and data-driven community disaster resilience.

4. Research objectives and questions

This research aims to improve and propose new ways to operationalize the multifaceted concept of community flood resilience using both nomothetic/top-down and idiographic/bottom-up methodological approaches in domain areas of community characteristics and capacities and leveraging new data (crowdsourcing geographic knowledge) to emphasize the role of techno-social co-evolution in scaling transformation and innovation in approaches to disaster resilience.

To achieve this aim, the three following objectives and related questions are dealt with:

First Objective: Quantification and benchmarking of the resilience baseline conditions by performing an index-based resilience measurement to be able to understand the pattern of urban flood resilience, underlying the contributing factors, and prioritizing interventions (Case study for this top-down approach: Iran, Tehran's 22 urban districts)

- **Question 1**: Which indicators should be incorporated into the flood resilience model and how should they be structured?
- **Question 2**: How to integrate the knowledge of local experts with different backgrounds regarding the importance of resilience criteria into the model?
- **Question 3:** What are the gaps and needs in such a top-down approach?

Second Objective: Understanding the capacities of VGI and crowdsourcing geographic knowledge for resilience enhancement and developing a framework as a guiding mechanism to utilize VGI toward scaling transformation in disaster resilience initiatives

- **Question 1**: What are the main aspects of VGI to be leveraged for facilitating transformative disaster resilience?
- **Question 2**: To what extent can the attributes of VGI support qualities of transformative resilience?

- **Question 3:** How can the identified VGI aspects be structured to provide a comprehensive framework for formalizing the process of adopting VGI for transformative disaster resilience?

Third Objective: Reflecting people's and stakeholders' perceptions and expectations (the wisdom of crowds) for improved disaster resilience by coding crowdsourced social media messages and open response texts from an online survey into relative topics within disaster phases in near real-time and compiling the extracted topics into five disaster resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) to understand the dynamics within large communities of individuals and the spatial extent of a situation within a timely situational (textual and spatiotemporal) analysis (Case study for this bottom-up approach: examining German Twitter data and results of and an online survey of flood responders as key stakeholder groups on the July 2021 flood disaster in Germany, parallel to the coronavirus pandemic).

- **Question 1:** How can the textual, spatial, and temporal features of tweets be extracted and analyzed to provide localized and timely information about the disaster situation?
- **Question 2**: To what extent can textual and spatio-temporal information extracted from social media contribute to improved situational awareness and collective disaster resilience to unforeseen disasters?
- **Question 3**: What are the main challenges and limitations to be considered in such social sensing approaches?

5. Research approach

The overall research approach consists of 3 main phases addressing 3 main objectives, starting with the benchmarking of resilience baseline conditions as the first milestone in understanding the factors and interactions that contribute to disaster resilience. In this phase, the theoretical background for measuring flood disaster resilience was established and a wish list for a set of indicators was developed based on an extensive literature review. Subsequently, a flood resilience index was developed based on the composite indicator building approach, and a new hybrid MCDM method for measuring flood resilience was proposed to operationalize the concept of flood resilience in the city of Tehran, Iran, as a case study.

After benchmarking baseline conditions for resilience, a framework for leveraging new data sources such as Volunteered Geographic Information (VGI) and crowdsourcing and facilitation of socio-technical co-evolution for transformative disaster resilience was designed and developed. Based on a qualitative content analysis of available resources, this phase explored key aspects of VGI use and proposed a comprehensive framework structured around the identified legal, institutional, social, economic, and technical aspects and capacities to formalize the process of adopting VGI in transformative resilience initiatives. This phase was undertaken to address the second research objective.

Having developed the general approach to using crowdsourced data to improve resilience, we needed to complement our understanding of how these new data sources could be used to capture the dynamics of disaster resilience with timely situational analysis and assess how this bottom-up, data-driven approach using social media crowdsourcing could complement the top-down approach to resilience conducted in the first phase. Therefore, in the final phase, social media crowdsourcing (representing public attitudes) was examined within disaster phases in near real-time by analyzing German Twitter data when the flood disaster hit Germany in July 2021. In addition to semantic/textual analysis (coding the obtained texts), spatio-temporal patterns of online disaster communication were assessed. As an additional data layer, an online survey of responders (key stakeholders in crisis management in Germany) involved in flood relief efforts was conducted with open-ended questions to determine their perceptions of issues and capacities to inform disaster resilience. An unsupervised ML approach was used to extract latent topics from the corpora of both data layers. The extracted topics were compiled into five themes related to disaster resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) to reflect people's and stakeholders' perceptions and expectations of improved disaster resilience. This collective real-time sensing approach was conducted to achieve the third research objective of contributing to the inclusive co-creation of knowledge and innovative and collaborative learning processes for improved collective disaster resilience.

6. Thesis outline

This thesis consists of seven chapters as shown in Figure 1.

Chapter 1: contains the motivation and the research gap, the research background, and the research problem. It also gives a general overview of the three underlying research objectives and the corresponding questions, as well as the research approach and the structure of the thesis, which gives an overview of the contributions, the main methods, and the research outcome.

Chapter 2: outlines the research design, methodologies approaches, and data sources used to answer the research questions and achieve the research objectives. This chapter explores the rationale for the chosen research methods.

Chapters three to five are the main parts and contain the contributions to the goal of developing new ways to assess and visualize flood resilience using new methods and new data:

Chapter 3: operationalizes the concept of urban disaster resilience and explores what constitutes disaster resilience and how to assess it. The measurement approach is based on the construction of a composite index based on the six resilience dimensions (social, economic, institutional, infrastructural, community capital, and environmental). A hybrid multi-criteria decision-making method is then developed to comparatively assess community resilience. The model was applied to assess and simulate the flood resilience of 22 districts in the city of Tehran, Iran. This provides decision-makers with a tool to prioritize actions to improve resilience.

Chapter 4: highlights the need for transformational approaches in disaster resilience when and where conventional and top-down resilience initiatives are less likely to deliver effective results, and therefore emphasizes the importance of inclusive co-creation of knowledge and innovative and collaborative learning processes. To support these transformative pathways, taking into account technological-social co-evolution and digital transformation, this chapter promotes the use of new data sources such as Volunteered Geographic Information (VGI) and crowdsourcing to fill the gap in capturing the spatiotemporal dynamics of disaster resilience. To gain a comprehensive understanding of the complexities and capacities of using these data, this chapter conducts a qualitative content analysis of available literature using the systematic concept-centric technique, Concept Matrix method, to explore key aspects of using VGI for transformative resilience, and proposes a comprehensive framework structured around the identified legal, institutional, social, economic, and technical aspects to formalize the process of adopting VGI in transformative resilience initiatives.

Chapter 5: provides new insight into the application of a bottom-up, data-driven and evidence-based approach to flood resilience enhancement and presents practical findings on how social media crowdsourcing and a near real-time collective sensing approach can address inductive disaster resilience capacities. Therefore, This chapter seeks to code near real-time social media messages into different topics within different disaster phases by mining German Twitter disaster-related tweets for 2021 flooding and pre-processing the raw data to perform textual, spatial, and temporal analysis. Moreover, as a complementary data source, an online survey was conducted in September 2021 among emergency responders and helpers to code the topics highlighted by this important stakeholder group. For text analysis, an unsupervised ML model was used and the spatio-temporal behavior of disaster-related tweet activity was analyzed. The extracted topics were finally compiled within different themes of resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) to reflect people's and stakeholders' perceptions and expectations for improved disaster resilience. This chapter highlights the importance of this timely social

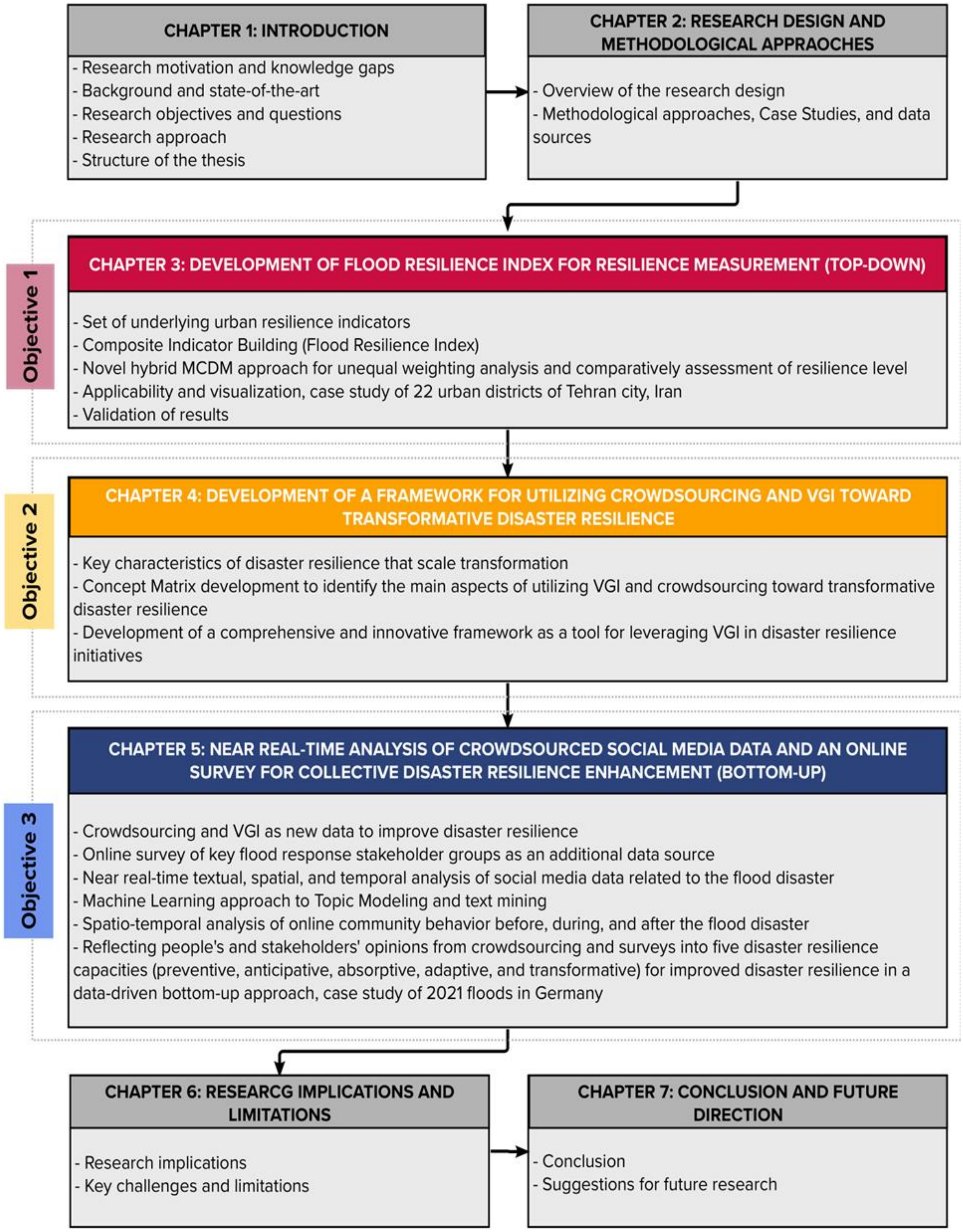

Figure 1: Research process and contributions of the dissertation

sensing approach for improved situational awareness and collective learning to strengthen community resilience to unforeseen disasters and shocks, but also to find transformative ways to prevent such climate-related disasters in the medium and long term.

Chapter 6: reports on the research implications from theoretical, practical, and research perspectives to highlight key contributions, followed by an overview of key challenges and limitations identified during the research process.

Chapter 7: The final chapter summarizes the main findings of this research, and reflects on the original research problem and the connections made in this study between top-down and bottom-up approaches to disaster resilience. It concludes with an outlook and suggestions for future research.

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CHAPTER 2

RESEARCH DESIGN AND METHODOLOGICAL APPROACHES

CHAPTER 2: RESEARCH DESIGN AND METHODOLOGICAL APPROACHES

1. Overview of research design

This chapter describes the research design and approaches used to answer the research questions and achieve the research objectives, which were defined based on the research context and problems previously stated in Chapter 1. Based on the overarching goal of this work to develop, test, and improve methods for assessing and strengthening community disaster resilience as a multi-faceted phenomenon, the research design consists of 1) literature reviews on both measuring disaster resilience and using crowdsourcing to strengthen disaster resilience, 2) the identification of research problems and gaps, 3) the establishment of overarching goal and objectives, 4) a mixed methods approach (in both nomothetic and idiographic assessments) and two case studies in Iran and Germany, 5) research outcomes as first, a top-down approach to resilience baseline indicators and a hybrid model to measure baseline conditions for flood resilience; second, a conceptual framework for using VGI and crowdsourcing data toward transformative disaster resilience; and third, a bottom-up approach for using new data and ML to improve collective resilience based on a real-time, data-driven model (capacity indicators). The detailed research design of each contribution can be described as follows:

In the first contribution, the mixed-methods approach is implemented in the case study, the city of Tehran in Iran. After extracting resilience indicators based on an in-depth literature review and developing a composite indicator, a hybrid MCDM approach is proposed using the analytical hierarchy process (AHP) and the technique for order preference by similarity to an ideal solution (TOPSIS) to first obtain a pairwise comparison of resilience indicators and their importance based on expert opinions, and then measure the status of resilience level in the 22 urban districts based on the developed resilience index. This type of assessment is nomothetic (or top-down) [36].

In the second contribution, a qualitative literature review is conducted using the concept matrix method as a systematic, concept-centered technique for the qualitative and content analysis of available resources. In doing so, various aspects of VGI and crowdsourcing data are identified and the role of VGI in transformative resilience is conceptualized by synthesizing the identified aspects and their relationships. As a result, a comprehensive synthesis framework for the use of VGI and crowdsourcing in disaster resilience initiatives is proposed.

In the third contribution, the case study approach is used to gain a comprehensive, detailed, and multifaceted understanding of flood resilience capacities, using a data-driven approach based on crowdsourcing data from German social media after the 2021 flooding and an online survey of flood responders to extract evidence-based factors that contribute to community-based and collective flood resilience improvement. This methodological approach is idiographic (or bottom-up) [36].

These new insights on the proposed approaches complement each other and demonstrate the importance of both top-down and bottom-up methodological assessments in studying community disaster resilience to capture both baseline and capacity indicators, considered as static conditions and dynamic resilience processes.

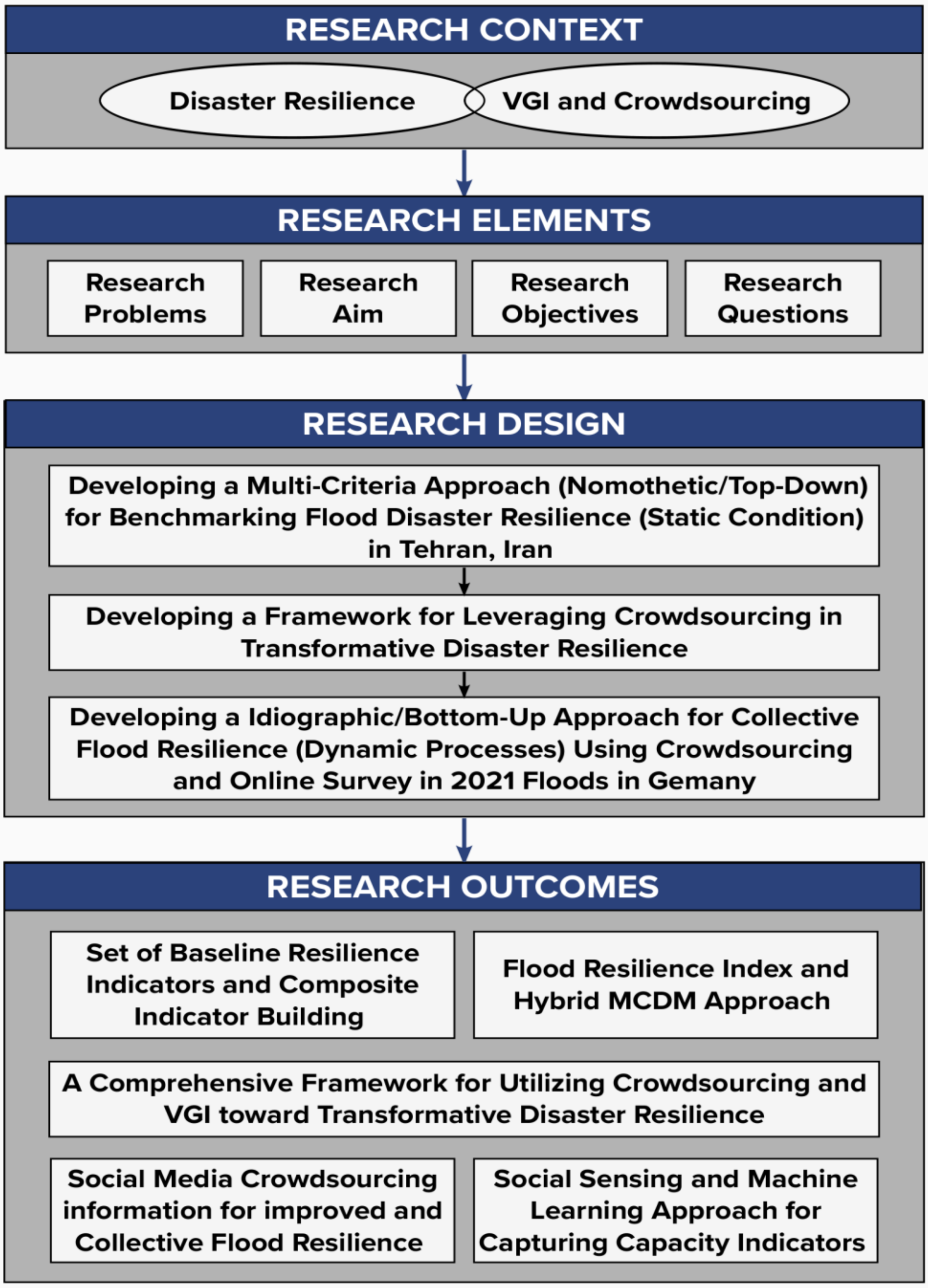

Figure 2: Overall Research Design

2. Methodological approaches, case studies, and data sources

Based on the overall goal of this thesis, the following methodological approaches were developed and various secondary and primary data sources in two case studies were used. The next subsections illustrate the methodology and materials developed and tested in the three contributions based on the three objectives and related questions mentioned in the previous chapter.

2.1 Composite Indicator Building and hybrid MCDM approach for benchmarking community flood resilience in Tehran, Iran

Methodological approach: Although it is difficult to find a standard procedure for the development of composite indicators for the operationalization of multi-faceted phenomena such as urban resilience, the majority of the relevant literature emphasizes the need for a flexible and transparent process [7,12,23,34,49–52] and therefore, the methodological approach in the first contribution consists of the following main steps:

1) Adopting a sound theoretical foundation as the basis for developing primary indicators: the BRIC model was chosen because, compared to the other models, it comprehensively covers six dimensions of community resilience (social, economic, institutional, infrastructural, community capital, and environmental) and takes a socio-ecological approach within spatial units for a multi-hazard context. In addition, it is one of the most widely applied frameworks in the literature for quantifying community resilience to disasters by indicators [90–92].

2) Identification and selection of sound, robust, and representative indicators: although this study uses the BRIC as the basis for creating composite indicators, it is not limited to the individual indicators presented by Cutter et al. [23,35]. To this end, valid and relevant indicators were identified based on an extensive literature review. The availability and scalability of data at the urban district level was carefully considered and those indicators that did not have one of the above metrics were eliminated from the primary list, and finally, the final set of eligible individual indicators was determined. [12,35,48,50].

3) Normalization of initial indicators and multivariate assessments for data reduction and factor retention: Minimizing the redundancy of highly correlated variables is an important step to avoid the problem of multicollinearity [12,93]. Pearson's correlation coefficient method was used to measure the strength of the relationship between the two indicators after the indicators were normalized. The following prioritization steps were taken for eliminating indicators with high correlation: (1) minimizing the reduction,

(2) balancing the number of indicators under each dimension, and (3) giving discretion to the researchers when neither of the first two steps was effective.

4) Weighting and aggregation of indicators using the hybrid MCDM method (AHP-TOPSIS): due to the fuzzy and multidimensional nature of resilience, the creation of flood resilience indicators is often supported by MCDM tools that can consider multiple criteria and different stakeholder perspectives. Accordingly, a hybrid AHP-TOSPSIS method was proposed. The AHP technique, which is based on pairwise judgment, was used to derive weights for each indicator [94]. AHP is one of the most applied knowledge-driven approaches due to its simplicity and flexibility in analyzing multiple criteria, especially when there are interactions among criteria [52,95,96]. TOPSIS is also a widely used technique for multicriteria decision-making because it can consider an unlimited number of alternatives and criteria [94]. This technique compares multiple alternatives in a compensatory approach based on the concept that "the ideal alternative has the best level for all attributes, while the negative ideal is the alternative with the worst attribute values" [97]. The logic of the TOPSIS approach reflects human decision-making behavior and is more realistic than non-compensatory methods. Also, the simultaneous consideration of the ideal and non-ideal solutions makes it a very useful technique in the MCDM process [98,99]. However, the TOPSIS tool does not provide a way to determine weights and due to this limitation, AHP is used to determine the weights of indicators.

5) Visualization and validation of results: Before visualization, the scores of the six dimensions and the overall disaster resilience index (DRI) are converted into the standard deviation from the mean using the Z-score method to categorize them into five main clusters. Then, the six resilience dimensions and the DRI were mapped to identify the spatial patterns of flood resilience. Finally, cross-validation was conducted to test the reliability of the empirical results of the hybrid method AHP-TOPSIS. Cross-validation is one of the main types of validation, which is based on comparing the results of the model used with the results of another model used to analyze the same problem [100]. Since the theoretical model used for this study was the BRIC, the results extracted with the developed model were compared with the results of the BRIC, where the indicators were considered equally important, on the same datasets. Pearson's correlation coefficient was calculated to investigate the possible relationship between the two results.

Case study: Operationalizing the concept of flood resilience is particularly important for Tehran, the capital of Iran because this megacity is vulnerable to floods because of its community's antecedent conditions (inherent vulnerability) and the types of flood hazards in this region (e.g., surface water flooding caused by extreme rainfall, flash flooding, and river flooding [101,102]. Tehran has a population of 8.43 million and 13.6

million in the metropolitan area [103] and ranks 10th among metropolitan areas prone to earthquakes and river flooding [104]. Although the frequency of flood events in Tehran has gradually increased over time, few studies have conducted flood-related urban disaster resilience analysis.

Flash floods, whether from river flooding or surface water caused by extreme rainfall, occurred frequently in Tehran due to the inability to properly drain rainwater and overload the drainage system. For example, reports of flash floods in Tehran indicate that in 2012 and 2015, heavy rains caused surface water flooding, killing eight and eleven people, respectively [118]. In 1965, a major river flood killed 2,150 people, and in 1987, torrential rains caused a flash flood that killed 1,010 people and injured about 1,027 [102]. Regardless of the characteristics of the hazard events, the antecedent conditions or inherent socioeconomic characteristics of the city show that Tehran is not immune to the forces of flooding. The city has 22 districts and a high concentration of industries, government organizations, services, and utilities, which makes coping with a natural disaster very complex [105]. In addition, Tehran has experienced rapid growth from 1976 to the present, with the highest positive net migration rate in Iran, mainly due to socioeconomic opportunities [106,107]. The expansion of built-up areas has led to an uncontrolled increase in impervious surfaces [108], which may increase the likelihood of flooding, especially during heavy rains. This study is, therefore, one of the first attempts to develop a flood resilience index for Tehran.

Data sources: the datasets used in this study are secondary administrative data sources that are publicly available: the Statistical Center of Iran, Tehran Municipality (Department of Planning and Architecture), Tehran Disaster Mitigation and Management Organization, Iran School Rehabilitation and Equipment Organization, and the data portal of the Iran Ministry of Health and Medical Education. The stepwise methodological approach and data sources are shown in Figure 3.

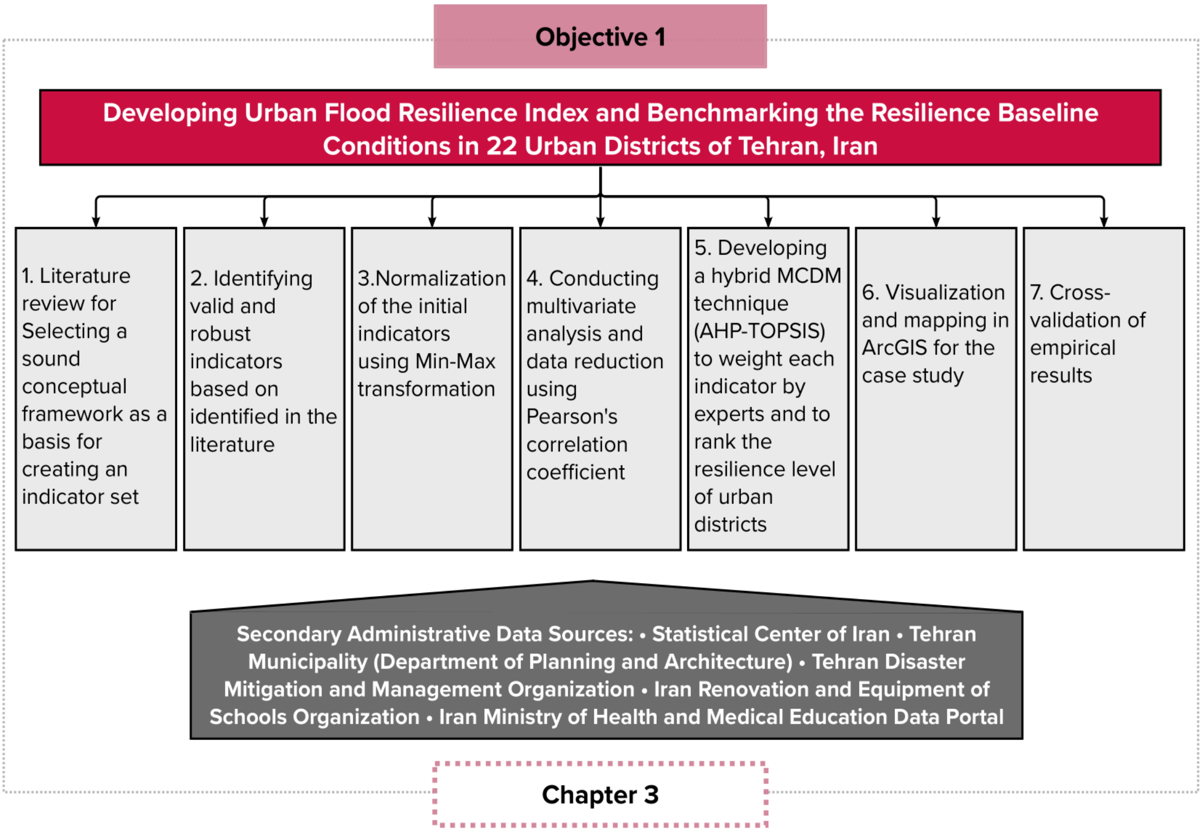

Figure 3: Stepwise methodological approach and data sources of the first contribution

2.2 Development of a conceptual framework for utilizing crowdsourcing and VGI toward transformative disaster resilience using decision matrix method

Methodological approach: As new crises of an unpredictable nature, such as extreme floods and pandemics, are likely to become more frequent, transformational interventions that leverage new data sources (e.g., crowdsourcing data) and innovative cutting-edge techniques (e.g., machine learning) can strengthen community resilience and mobilize the creativity and engagement needed to address crises. However, leveraging crowdsourced information and VGI for transformative resilience involves multiple aspects and involves multidisciplinary bodies of knowledge. While previous studies have discussed the opportunities and challenges associated with using crowdsourcing for disaster resilience, they have notably lacked a conceptual framework, leaving the overall picture of crowdsourcing and VGI for urban resilience unclear. Therefore, any attempt to use these data for transformative resilience requires a fundamental understanding of their aspects in line with the characteristics of transformative resilience. The following major steps were then followed to create a conceptual framework after identifying fundamental elements of urban resilience that scale transformation:

1) Selection of primary studies: for research done in the previous ten years, databases were searched using the search strings "Volunteered Geographic Information," "disaster resilience," and "transformation." Three inclusion criteria guided the selection of studies: (i) it corresponds to the keywords, (ii) it describes a sort of transformation brought on by VGI and crowdsourcing, (iii) it discusses the added value or drawbacks of VGI in disaster resilience. Articles that just addressed the VGI itself (such as OSM or Twitter) without mentioning any part of VGI that contributes to the transformational processes in disaster resilience were eliminated as an exclusion criterion.

2) Identification and extraction of concepts: the "Concept Matrix" approach was used as a systematic concept-centric technique for the qualitative and content analysis of available resources to enable the synthesis of the literature [109,110]. The left column of the matrix was used to list references, and the titles of each column were chosen to correspond to the recognized topics in the literature. The selected ideas were coded utilizing the inductive coding technique (first coding cycle), which gradually evolves throughout the study of the material without the use of a preexisting coding scheme and is often impacted by the research objectives [111]. Each time a new concept was found, another column was added to the matrix. In this case, the concepts discussed in previous studies were recorded in a concept matrix, which then allowed for a comparative analysis of all studies [112].

3) Organization and grouping of concepts: Pattern coding (second coding cycle) [113] was carried out in accordance with the authors' scientific and conceptual reasoning in order to generate schematic higher-order themes for creating the synthesis framework was carried out according to characteristics, assumptions, and highlighted themes under main aspects to obtain schematic higher-order themes for building the synthesis framework [110,114]. This facilitates the creation of a cognitive map for comprehending the interactions by condensing the information from the first coding cycle into insightful and manageable units of analysis [111].

4) Conceptualization: a conceptual framework is a tool that includes a collection of logical components and their connections. As a result, by combining the ideas and connections found in the earlier phases, a thorough framework was presented to instruct academics and practitioners on how to utilize VGI in disaster resilience initiatives.

Data sources: Literature search based on studies published between 2010 and May 2021 extracted from Google Scholar, Web of Science, and Scopus. From 414 hits, 82 relevant studies were selected. The stepwise methodological approach and data sources are shown in Figure 4.

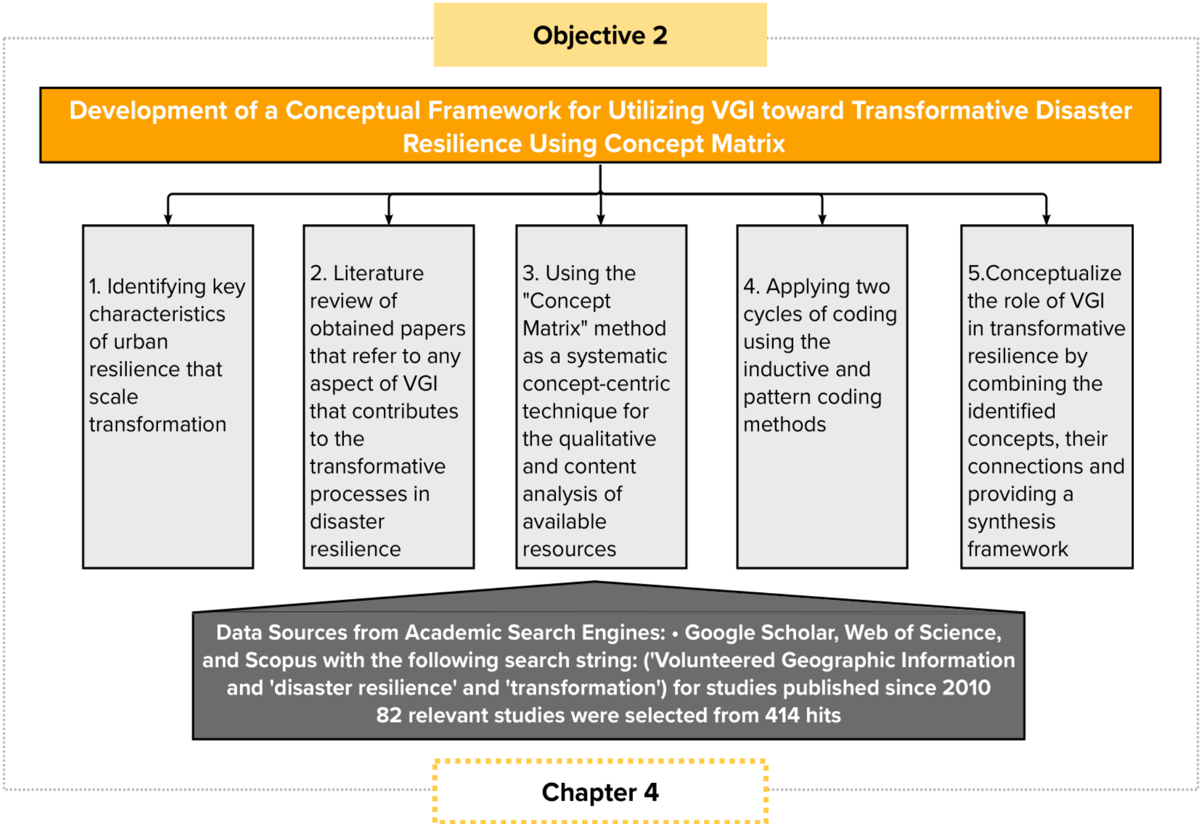

Figure 4: Stepwise methodological approach and data sources of the second contribution

2.2 Semantic and spatio-temporal analysis of social media crowdsourcing for strengthening disaster resilience, the 2021 flood in Germany

Methodological approach: To capture the dynamic processes of resilience, this study seeks information, insights, concerns, and opinions from public discourse and responses in online communities and their spatiotemporal behavior in real-time, and gathers and analyzes local knowledge to improve situational awareness and contribute to data-driven disaster resilience. In this context, Twitter as an open-source microblogging platform was used as a crowdsourcing data source to extract the 2021 flood-related tweets in Germany. Twitter is a valuable and useful source of data because each tweet is typically linked to temporal-spatial and textual information, resulting in relatively homogeneous and comparable corpora for understanding dynamics within large communities of individuals due to the relatively short message size [66,115]. To include stakeholder perspectives in the analysis, an online survey with open-ended questions was conducted among key stakeholders after the flood. The following key steps were then taken to obtain and analyze these data:

1) Twitter data collection and processing: after collecting related tweets, deleting duplicates, and translating from German to English, the entire corpus from the data mining phase was preprocessed (4842 tweets and 1729 georeferenced tweets remained). Preprocessing is required to remove noisy data, enhance data quality, and

improve keyword generation in the analysis [116]. It consists of transforming the data (removing punctuation, emails, URL links, numbers, and emojis, and converting the text to lowercase), normalizing (using lemmatization to create the root form of inflected words), and filtering (deleting stop words such as 'the', 'on', etc.).Then, N-grams (bi-gram and tri-gram) were used to find frequently occurring words in the document, and term frequency-inverse document frequency (TF-IDF) was used to assign a weight to each word based on word frequency to balance the importance of the word in the tweets and in the corpus. The cleaned tweets were tokenized to convert them into words for further analysis [117].

2) Spatial and temporal analysis: the disruptive situation is dynamic, and so are the associated human responses, such as the frequency of social media communication [67]. The frequency of tweet activity (the hourly volume of relevant tweets) and a burst of tweet activity may indicate a change in the situation or a major impact of the disruption on people or places. Therefore, the hourly volume of tweets was calculated to better capture the dynamics of the flooding situation within the time period studied and to detect changes over time.

In addition, each tweet is associated with a location, and the distribution of geolocated or geotagged tweets can provide an estimate of the locations and extent of the disruption and provide information about the situation. The more geotagged tweets posted in the same area, the greater the damage and the more negative the impact of the disruption [67]. Thus, Kernel Density Estimation (KDE) was used to better estimate the extent of the disturbance by aggregating point-based observations into grid cells with administrative bounding polygons. KDE of tweets is a promising technique for estimating the density of tweets because it belongs to a nonparametric analysis with no fixed structure and depends on the point data [118]. As shown in existing studies, the activity of geotagged tweets is closely related to physical damage during disasters [119].

3) Semantic (textual) information analysis: Topic Modeling is one of the most powerful techniques in text mining for detecting latent data and finding correlations between data and text documents, with Latent Dirichlet Allocation (LDA) being one of the most popular techniques in this area [120]. LDA is an unsupervised ML method and a generative probabilistic model and it was applied to the final set of cleaned tweets using the Gensim library to analyze the unstructured textual information from the tweets and identify the topics associated with the flood. A topic refers to a group of words with similar or closely related meanings under certain probabilities. If the author of the document (the tweet) is a person, these topics reflect that person's perspective and vocabulary. We examined the composition of words in these automatically generated topics for each phase and manually assigned the semantic labels

considering the authors' domain knowledge and consensus [87]. LDA was also applied to the survey results.

4) Validation of the model: to validate the LDA model, the perplexity and coherence measures are applied. The perplexity score is intuitively based on the degree of surprise a trained model experiences when confronted with unfamiliar documents after the learning phase. Lower perplexity indicates a better generalization ability of the model [121]. On the other hand, the coherence value has been proposed to better reflect the correspondence between numerical scores and users' perception of the quality of topic models [122]. The higher the topic coherence, the better the topic is interpretable by humans [87]. Thus, we used these two measures in tuning the hyperparameters k, α, and β for which the highest coherence value is obtained, resulting in a more meaningful topic selection for tweets than would be the case with randomly chosen hyperparameters.

5) Visualization: pyLDAvis was used to visualize the results obtained from crowdsourcing. This tool was developed to help users interpret the topics in a topic model fitted to a textual corpus of data in an interactive web-based visualization [123]. Compared to traditional clustering techniques, where each tweet can only belong to a single topic, an advantage of pyLDAvis is that a word can be clustered to different topics. For example, the word ‘water-level’ may appear in a context related to situational information or emergency operation. In this case, it can better represent the nature of the language [117,123]. For the survey results, Word Cloud was used as the visualization tool.

6) Compilation of extracted topics into five resilience capacities: since social media and surveys have shown high potential for providing factual, organizational, and psychological content [87], we compiled the data-driven topics from the previous steps under the five resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) as overarching themes based on the DRIFT framework [27]. The compilation of topics reflects collective intelligence (near real-time insights from online communities, people, and stakeholders regarding the flood disaster), and illustrates the resilience capacities of the community.

Case study: according to the International Disaster Database (EM-DAT), the July 2021 flood in Germany was the tenth worst in Europe in the previous 100 years [4]. A slow-moving large summer storm system named 'Bernd', whose size and moisture are attributed to climate change, resulted in high rainfall -up to 150-200 mm in 48 hours- and corresponding peak runoff [124]. The flooding affected about 40,000 people, claimed more than 197 lives, and 1000 injuries, and caused total damage of about $40 billion [4]. Although Baden-Württemberg, Bavaria, Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Saxony, Saxony-Anhalt, and Thuringia were all affected, the worst flooding occurred in the western states of Rhineland-Palatinate and North Rhine-Westphalia on July 14, and in Saxony and Bavaria in the south on July 17 [4,125]. While riverine flooding is more common and minor pluvial flooding has occurred frequently in these states in recent years, pluvial flood damage on this scale was exceptional. Most importantly, the high death toll was unexpected and shocking in an industrialized country that had never seen such a high death toll and destruction and raised questions about the resilience of Germany to floods and its readiness to deal with the impacts of climate change. Similar to other flood disasters in other countries, a public debate about questions of responsibility and blame soon began, and disaster management came under criticism from the media and the people [126]. Therefore, leveraging a collective real-time sensing approach using social media crowdsourcing and a survey can provide valuable information, ranging from early identification of necessary measures to insights for developing resilience strategies to increase evidence-based resilience to unforeseen disasters.

Data sources: The data for this study came from two sources. First, crowdsourcing data from social media (German Twitter) from July 12 to July 31, 2021, using an academic API (application programming interface) and a set of hashtags defined before, during, and after the flood event to analyze flood-related tweets. A total of 6640 tweets were obtained, of which 1810 tweets were geo-referenced. Second, from September 1 to September 21, 2021, [126] conducted an online survey among emergency responders and relief workers. The online survey was carried out using the SoSciSurvey online tool and consisted of 31 questions, including 24 closed-ended questions and 7 open-ended questions. The survey preliminary analysis was published in [126]. However, in the third contribution, an in-depth analysis of the open-ended response texts to 7 open-ended questions in the survey was conducted to potentially uncover additional problems, suggestions, concerns, positive experiences, and areas for improvement by capturing direct open opinions and expressions. The open-ended response fields were used by 911 respondents and 37,400 words of text (approximately 94 pages) were collected. The stepwise methodological approach and data sources are shown in Figure 5.

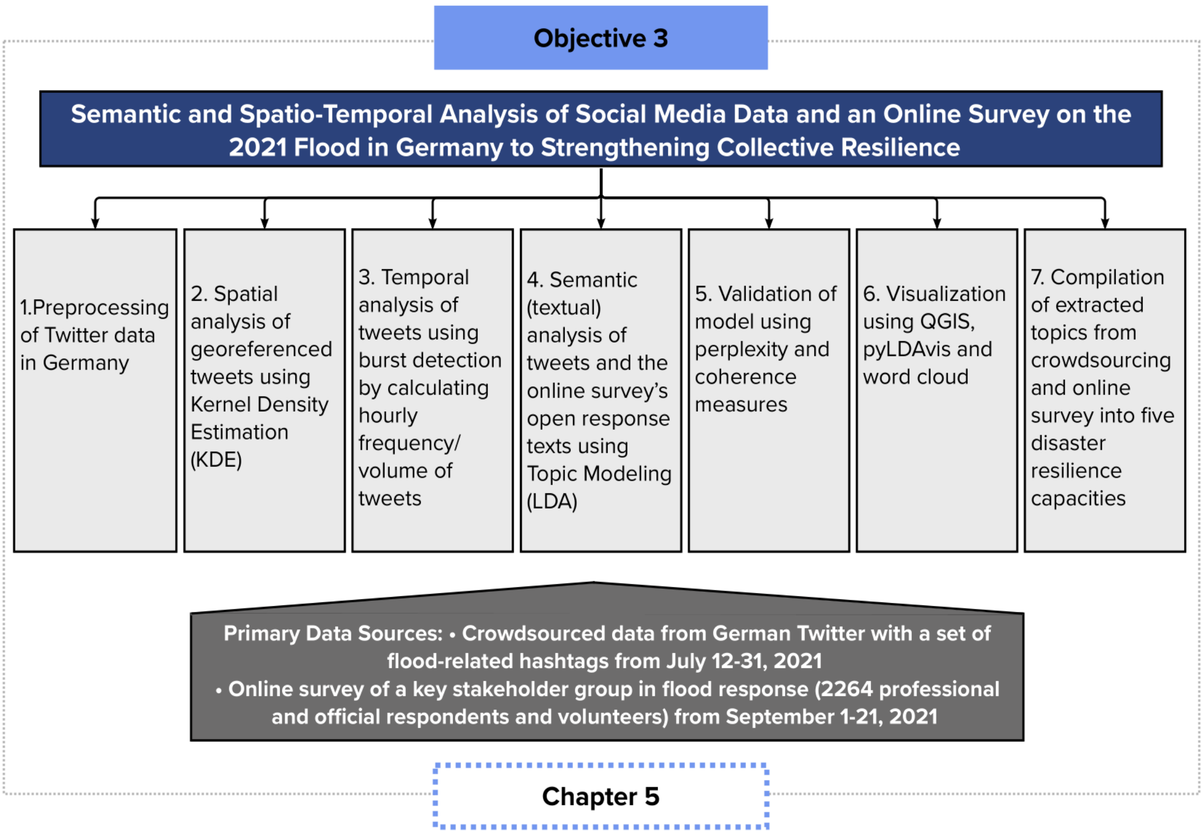

Figure 5: Stepwise methodological approach and data sources of the third contribution

3. Ethical Consideration

Considering the ethical aspects aimed at protecting the individuals, communities, and environments involved in the studies from any form of harm, manipulation, or misconduct, the information from the case studies, tweets, and online survey was kept confidential and used only for research purposes. It is also important to note that the views expressed by the experts and the people were personal views and do not represent the views of any organization.

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CHAPTER 3

DEVELOPMENT OF FLOOD RESILIENCE INDEX (NOMOTHETIC/TOP-DOWN APPROACH)

This chapter benchmarks the concept of urban flood resilience using a nomothetic/top-down approach. Although the measurement of urban resilience to disasters has attracted much attention recently, there has been no optimal approach for operationalizing this concept. Therefore, this study develops a transparent and new approach to assessing resilience to flooding. The benchmarking approach is based on the construction of a composite flood resilience index composed of six resilience dimensions: social, economic, institutional, infrastructural, community capital, and environmental. After extracting resilience indicators based on an in-depth literature review, a hybrid multi-criteria decision making method was developed. The method used is a combination of the AHP for prioritizing and weighting the selected indicators by experts and the TOPSIS tool for ranking Tehran districts based on their resilience level as a case study. Such place-based assessments provide an opportunity to monitor the inherent characteristics of resilience over time and provide decision makers with a tool to integrate resilience thinking into urban development and resilience-oriented urban planning.

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A multi-criteria approach for assessing urban flood resilience in Tehran, Iran

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ABSTRACT

Operationalizing the concept of urban disaster resilience is a major milestone toward understanding both the characteristics that contribute to the resilience of cities to natural hazards and the interactions required to build and sustain it. While the measurement of urban disaster resilience has recently gained much attention, there is so far no optimal approach for operationalizing this concept and therefore there is a need to conduct more empirical studies on what constitutes disaster resilience and how to assess it. In this study, a resilience assessment focuses on the inherent characteristics and capacities of Tehran in the context of flash floods from surface water or from the overflow of rivers. The measurement approach is based on constructing a composite index based on six resilience dimensions social, economic, institutional, infrastructural, community capital and environmental of community flood resilience. This follows by developing a hybrid multi-criteria decision-making method. The applied method is a combination of the AHP for prioritizing the selected indicators and the TOPSIS tools in order to get Tehran's urban districts ranked based on their resilience levels. Data were mostly from the Statistical Center of Iran and Tehran Municipality's accessible data sources. The results clarify that Districts 6 and 22 are comparatively the most resilient districts, while District 1 is the only district with the lowest level of resilience. Such place-based assessments have an opportunity to track community performance over time and provide the tool to decision-makers in order to integrate resilience thinking into urban development and resilience-oriented urban planning.

1. Introduction

In recent years, cities are confronted with increasing risks posed by natural and climate-induced hazards. Since urban communities are at the forefront of the impacts of hazards and the associated losses, international academic and policy circles have acknowledged the need to strengthen cities' resilience [1–5]. Moreover, there are now local to global interests in resilience as a mechanism for enhancing the capacity to cope with environmental changes and disturbances at different geographical scales such as cities [6–10]. While the term resilience has received attention from different scientific communities over time, finding an agreement upon a standard definition of resilience in the literature is problematic [11–17]. However, the concept of urban resilience is defined as the concept that enhances the ability of cities to face adverse events and consists of inherent and adaptive capacities of them to respond, adapt and grow no matter what kind of disturbance they experience [9,10,15,18,19].

Since urban resilience is a complex concept and difficult to operationalize, developing a technique or method to actualize the concept would be a major milestone toward understanding factors and interactions that contribute to, build and sustain resilience [12,20–24]. Theoretical frameworks and assumptions of disaster resilience are abundant, including a variety of approaches that have been developed to operationalize urban resilience at different geographical scales and hazard contexts [12,25,26]. Despite the fact that there is no standardized approach to measure disaster resilience, the disaster resilience of place (DROP) model developed by Cutter et al. (2008) to improve comparative assessments of disaster resilience at the local or community level, and highlighted the need for more empirically and evidence-based researches on urban resilience assessment [27]. The DROP model is often considered as one of the well-known conceptual frameworks focuses on antecedent and inherent conditions within communities and underscores the role of absorptive and coping capacities for building and enhancing disaster resilience [15,19,28–30]. The operationalized version of the model called "the baseline resilience indicators for community" (BRIC) framework [15,31] was the first trying of the model to pass from a theoretical framework to an operationalized practice. The BRIC framework considers the concept of community resilience as

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both pre-event inherent resilience (robustness) and post-event adaptive (transformation) resilience [15]. According to Asadzadeh et al. (2017) and Sharifi (2016), the BRIC includes extensive coverage of community resilience dimensions compared to the others, with a socio-ecological approach within spatial units for multi-hazard context. In addition, it is one of the most applied frameworks within the existing literature on quantifying community disaster resilience through index creation [28,32,33].

Moreover, considerable attention is given to the construction of a composite indicator for benchmarking the concept [6,20,30,34–40]. A composite indicator "aggregates multiple individual indicators to provide a synthetic measurement of a complex, multidimensional, and meaningful phenomena" [24]. This approach assesses and compares resilience level within particular communities for any geographical areas and ranks them from the most to least resilient [31,41].

Although finding a standard procedure for developing composite indicator is difficult due to the variety of theoretical foundations, the majority of related literature emphasizes the need for a flexible and transparent process that comprises of the following steps [15,20,24,25,42–45]:

1. Developing or applying a sound theoretical foundation as a basis for primary indicator building
2. Identifying and selecting indicators that are sound, robust and related
3. Using multivariate assessments for data reduction and factor retention
4. Weighting and aggregating indicators
5. Visualizing and mapping results
6. Validating results to ensure reliability

Several quantitative methods have been developed to construct a composite indicator in order to measure urban disaster resilience. A valid and reliable composite index starts with either development or application of a sound theoretical foundation as a basis to form primary indicators [24,31,43]. Although a sound theoretical framework enables researchers to enhance their perception of the subject to be operationalized, it affects the decision of what should be measured (resilience of what), for what purpose (as a dynamic concept or static result), and when (long-term process and capacity building or short-term persistence and result) [19,46]. Assessment of urban resilience should answer the question of why the resilience assessment is being performed and what the assessment should ideally achieve. While the distinction between process-oriented (measuring a set of capacities and processes) and result-oriented (measuring a set of characteristics or assets) assessments characterize the literature [6,20,25], it is also argued that resilience is a dynamic process and assessment frameworks need to conceptually consider both the static features and dynamic processes [29,47–50]. However, most of the existing measurement approaches view resilience as either an outcome (result-oriented) or process (capacity building process), and only a few numbers of them such as the BRIC model (2014) view the term as both absorptive (robustness) and coping capacities (adaption) simultaneously [15]. This is a major challenge for urban resilience assessment because primary indicators selection is based on these assumptions and underlying factors. . In addition, while there are different approaches to the arrangement of primary indicators within resilience sub-components (dimensions), deductive (theory-driven) and inductive (data-driven) approaches are broadly used in the literature. Deductive reasoning specifically has the potential to identify the best possible indicators and explain the relationships between a specific set of concepts and theories [24,38,51].

The weighting of individual indicators or dimensions, which is another challenging issue in this process, reflects the relative importance of each indicator regarding a subject under scrutiny [15,52–54]. Although equal weighting is the most prevalent technique in constructing composite indicator, it may fail to capture the interconnectedness of indicators in such a multi-dimensional phenomenon [24,43,45,54]. However, when there is sufficient knowledge on the relative importance of indicators, applying unequal weighting method may provide an empirical assessment based on local experts' opinion and local needs [24,55,56]. Since urban resilience is a multifaceted concept, the significance of particular criteria may vary between different contexts and scales. Therefore, by applying an unequal weighting method, we can integrate the knowledge of experts from different disciplines (qualitative assessment) into a theoretical and quantitative analysis.

In the absence of standards (thresholds) for resilience indicators, multi-criteria decision-making (MCDM) tools would help in explaining the conceptual significance of each factor and identifying the trade-off among various criteria. Furthermore, MCDM approaches can provide not only a comparative assessment but also assist decision-makers to construct and evaluate the best solution (alternative) [57–60]. In this regard, the applied methodology in this study is a hybrid MCDM approach using analytical hierarchy process (AHP) and the technique for order preference by similarity to an ideal solution (TOPSIS). While AHP allows evaluating the components by pairwise comparison and obtaining the weights, TOPSIS orders the solutions based on the idea of maximizing distance from the negative-ideal solution (least resilient) and minimizing the distance from the positive ideal solution (most resilient). Thus, the best solution is the closest one to the ideal point [61].

Therefore, this study represents one of the first attempts to develop an index-based measurement using a hybrid AHP-TOPSIS method for comparative assessment of flood resilience for Tehran, the capital city of Iran. Operationalizing the concept of flood resilience is particularly important for Tehran in light of the fact that this mega city is vulnerable to floods because of its community' antecedent conditions (inherent vulnerability), and different types of flood hazards in this region (e.g., surface water flooding caused by extreme rainfall, flash floods and river floods [62,63].

2. Research design and method

In this study, the resilience assessment scheme focused on the inherent characteristics and capacities of the place (22 urban districts of Tehran) and was utilized through an index-based approach. We tended to provide a baseline on existing characteristics of the 22 urban districts according to six resilience dimensions (social, economic, institutional, infrastructural, community capital and environmental) based on a common set of sound and specific indicators. The represented datasets for the indicators were obtained mainly from the Statistical Center of Iran as the unique authority of the country's official statistics [64]. The other required data were retrieved from publicly accessible data sources of Tehran municipality (Department of Planning and Architecture), Tehran Disaster Mitigation and Management Organization, Renovation and Equipping Schools of Iran and Ministry of Health and Medical Education of Iran. The Disaster Resilience Index (DRI) was constructed through the following steps (see Fig. 1):

2.1. Selection of a sound conceptual framework as a basis for indicator building

The baseline resilience indicators for community (BRIC) framework [15,31] was selected as the theoretical foundation for primary indicator building. It embraces six dimensions: social, economic, institutional, infrastructural, community capital and environmental elements [15,31]. It proposes a set of indicators for each dimension that can be deployed to measure the baseline characteristics and the present-day features of communities to inform decision-makers on the overall level of disaster resilience of the place. In this study, social resilience refers to social capacity within and between communities that affect their ability to cope with natural hazards [30,31,43]. Economic dimension measures the vitality, redundancy, and resourcefulness of the community economy [15,30]. Institutional resilience can be measured based on the

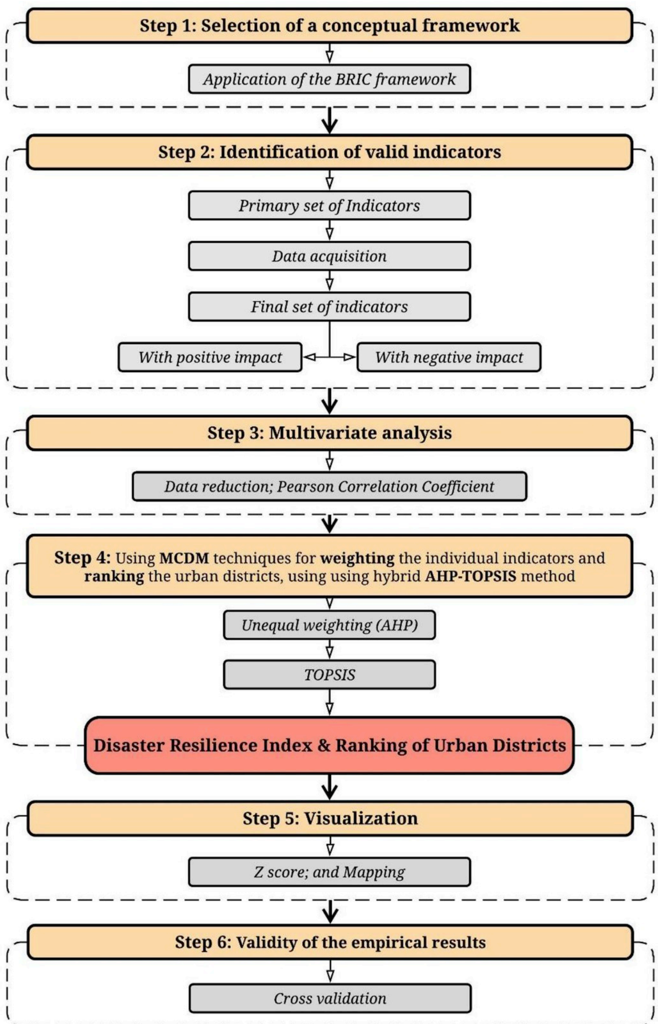

Fig. 1. Stepwise methodological approach for constructing DRI in the study area.

attributes connected with planning, preparedness initiatives and institutional ability to adapt to rapid changes [30,31,43]. Infrastructural resilience is about the attributes or qualities of physical assets leading to response and recovery capacity, and community capital refers to the degree of the linkage between individuals and their larger neighborhoods [15,31]. Environmental dimension considers, on one hand, the chronic environmental degradation caused by human activities, on the other hand, the qualities of the urban environment that increase the absorptive capacity in the context of flooding [15].

2.2. Identification of valid indicators

Although this research adopts the BRIC as the basis for the composite indicator building, it is not limited to the individual indicators presented by Cutter et al. (2010, 2014). For this purpose, based on existing literature, such as the 'PEOPLE' framework [30], 'City Resilience Index' framework [9], 'MISR' framework [36], relevant, robust and representative indicators were identified. In addition, availability and scalability of data in the level of the urban district were carefully checked, and as such, those indicators without one of the mentioned metrics were eliminated from the primary list and lastly the final candidate set of individual indicators were defined [24,31,41,43].

2.3. Multivariate analysis and data reduction

The problem of multicollinearity may occur if the indicators have strong inter-correlations. Thus, minimizing the redundancy of highly correlated variables is an important step [24,65]. Pearson's correlation coefficient method was used to measure the strength of the relationship between the two indicators. According to Samuel & Okey (2015) [66], correlation coefficients greater than 0.8 can be considered significant. For elimination of indicators with high correlation, the following prioritization steps were taken: (1) minimize reduction; (2) balance between the numbers of indicators under each dimension; and (3) allow for researchers discretion where none of the first two steps were effective.

2.4. Using MCDM techniques for weighting the individual indicators and ranking the urban districts using hybrid AHP-TOPSIS method

The first objective in this step is to integrate the knowledge of local experts into the analysis. Therefore, five experts were selected from governmental organizations, universities and private consulting companies dealing with disaster risk management in Tehran. In order to derive weights for the individual indicators, we applied the AHP technique [67]. The AHP process is based on pairwise judgment. It is, moreover, one of the most applied knowledge-driven approaches due to its simplicity and flexibility for multiple criteria analysis particularly where there are interactions between criteria [45,57,68]. In this regard, a pairwise judgment was made on the individual indicators and the experts were asked how important they would think different criteria are. Their comparison between each indicator was made by using the numerical scale of Saaty from 1 to 9 (see Table 1) which indicates the relative importance of the indicator [67,69]. Moreover, due to the issue of inconsistencies in the process of pairwise comparisons, consistency ratio (CR) needs to be determined. If CR does not exceed 0.1, the expert's judgment is acceptable. Finally, after extracting the relative importance of any individual indicators, the average weights were calculated as the final weights of each indicator.

The second and ultimate objective is to compare and rank the urban districts of Tehran based on their resilience level. To this end, the TOPSIS technique was utilized. TOPSIS is a widely employed technique for multi-criteria decision-making processes because of its simplicity and ability to consider a non-limited number of alternatives and criteria [57]. This technique compares multiple alternatives in a compensatory approach based on the concept that "the ideal alternative has the best level for all attributes, whereas the negative ideal is the alternative with all of the worst attribute values" [60]. Its logic represents the rationale of human choice, that is more realistic than non-compensatory methods and likewise, its simultaneous consideration of the ideal and the non-ideal solutions make it a very useful technique in the process of MCDM [70,71]. However, the TOPSIS tool does not provide weight elicitation. Due to this limitation, the weights were obtained from the AHP. Fig. 2 illustrates the schematic diagram of the applied hybrid method.

According to Yoon & Hwang, (1995) [72], TOPSIS method can be expressed in a series of following steps:

(1) Construct the decision matrix (DM)

Table 1
Saaty's pairwise comparison scale; Sources: (Saaty, 1987).

Verbal judgment	Numerical rating
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values	2, 4, 6, 8

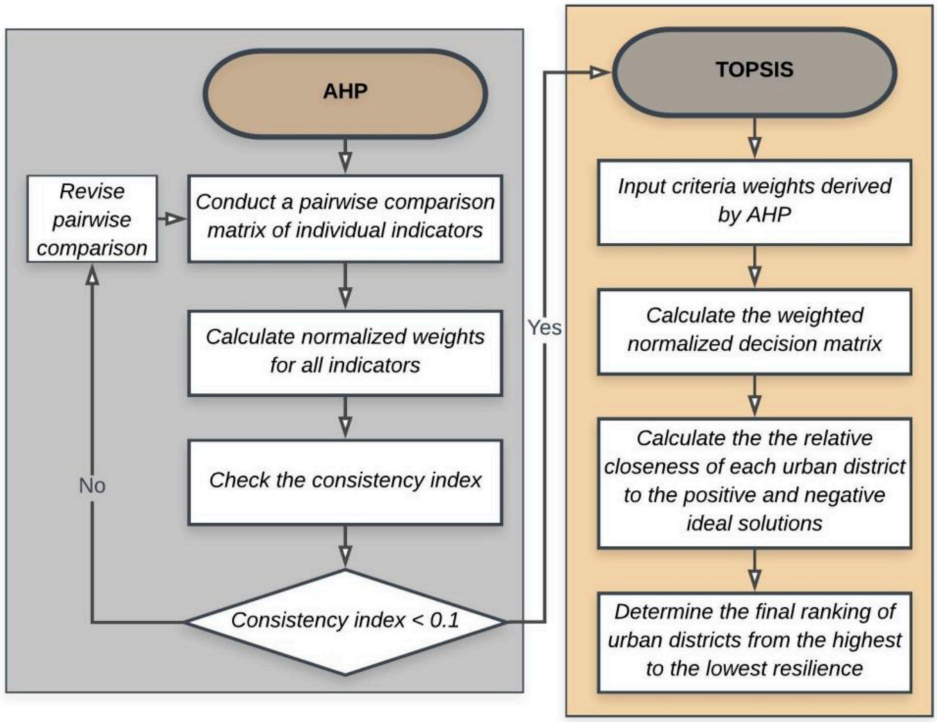

Fig. 2. Schematic diagram of the hybrid MCDM method.

The elements (x_{ij}) of the matrix are related to the value of indicator i (i = 1, …m) with respect to urban district j (j = 1, …n). The elements I_1, I_2, … I_n refer to Indicators while D_1, D_2, … D_n refer to the urban districts.

$$\begin{array}{cccc} I_1 & I_2 & \cdots & I_n \end{array}$$

$$DM = \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{21} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

(2) Calculate the weighted normalized decision matrix.

This step transforms various attribute dimensions into non-dimensional attributes through the equation below. Normalized decision matrix (NDM) allows comparison across indicators with different units.

$$NDM = r_{ij}\frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}$$

The weighting decision matrix was constructed by multiply each element of each column of the normalized decision matrix by the obtained weights from the AHP method.

$$V = v_{ij} = w_j\, r_{ij} \quad \text{for (i=1, …m); (j=1, …n)}$$

where W_j is the weight of the j-th criterion, $\sum_{j=1}^{n} w_j = 1$.

(3) Determine the positive ideal and negative ideal solutions.

The positive ideal (A^+) and the negative ideal (A^-) solutions are defined according to the weighted decision matrix via the equations below.

$A^+ = \{v_1^+, v_2^+ \ldots, v_n^+\}$, where: $V_j^+ = \{(\max_i (v_{ij})$ if $j \in J)$, $(\min_i v_{ij}$ if $j \in J')\}$

$A^- = \{v_1^-, v_2^- \ldots, v_n^-\}$, where: $V_j^- = \{(\min_i (v_{ij})$ if $j \in J)$, $(\max_i v_{ij}$ if $j \in J')\}$

where J is associated with the beneficial indicators and J′ is associated with the non-beneficial indicators.

(4) Calculate the separation distance of each district from the ideal solution and non-deal solution.

The separation of each alternative from the positive and negative ideal solutions are given as

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (V_j^+ - V_{ij})^2} \quad \text{(i=1,2, …m)}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (V_j^- - V_{ij})^2} \quad \text{(i=1,2, …m)}$$

(5) Calculate the relative closeness of each urban district to the positive ideal solution that means the highest level of flood resilience.

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \quad 0 \le C_i \le 1$$

(6) Rank the preference order

The higher value of Ci represents the higher resilient district. Thus, the 22 urban districts were compared and sorted accordingly.

2.5. Visualization and mapping

The next step after constructing composite flood resilience indicators is the visualization of the results. Prior to visualization, the scores of the six dimensions and overall disaster resilience index (DRI) were categorized across five major clusters using the Z-score method to identify the spatial patterns of flood resilience. This method transforms the scores to the standard deviation from the mean. Afterward, six resilience domains maps, as well as the final map for DRI were produced.

2.6. Validity and reliability of the empirical results

Last but not least step in composite indicator building is validity and assessing the reliability of results. The degree to which the measurement approach in this study succeeded in quantifying the resilience index and to obtaining reliable results can be tested. “Validation is a set of methods for judging a model's accuracy in making relevant predictions that information can be used by decision makers to determine the results' applicability to their decision” [73]. In this study, cross-validation was performed to test the reliability of the empirical results obtained by hybrid AHP-TOPSIS method. Cross validity is one the main types of validation (e.g. face validity, internal validity, external validity, and predictive validity), based on the comparison of results of the model in use with the results of another model analyzing the same problem. Since the deployed theoretical model for this study was the BRIC [15], the results extracted by the hybrid AHP-TOPSIS method were compared with the results obtained from the BRIC, in which the indicators were taken to be equally important, on the same datasets. For investigation of the possible relationship between the two obtained results, Pearson's correlation coefficient was calculated.

2.7. Study area

Tehran has a population of 8.43 million, and 13.6 million in the greater metropolitan area [74]. Tehran is ranked as the 10th metropolitan areas at risk from earthquakes and river floods [75]. While the frequency of flood events increased gradually over time in Tehran (see Table 2), few studies have operationalized a flood-related analysis of urban disaster resilience.

Geomorphological characteristics of Tehran consist of three main sections: mountains in the north, Piedmont zone in the center and desert in the south. These geological sections shape the number of rivers and watercourses rising from the north and flowing through the city that are potential flood channels (Fig. 3) [76]. Therefore, flash floods whether from the overflow of rivers or from surface water caused by extreme rainfall accrued frequently in Tehran because rainwater is unable to be properly drained and overwhelms the drainage system. Table 2 shows the reported flash flood events in Tehran. For instance, in 2012 and 2015 heavy rainfall resulted in surface water flooding, killing eight and eleven people respectively [63]. In 1965, a huge river flood killed 2150 people and in 1987 torrential rain caused a flash flood that left 1010 dead and approximately 1027 injured.

Regardless of the hazard event characteristics, the antecedent conditions or inherent socio-economic characteristics of the city demonstrate that Tehran is not immune to the forces of floods. The city has 22 urban districts and a high concentration of industries, governmental organizations, services, and utilities that make it a very complex case to be managed when a natural disaster occurs [77]. Furthermore, Tehran has experienced a rapid growth rate from 1976 to the present, with the highest positive net migration rate in Iran mainly because of socio-economic opportunities [78,79]. A massive construction boom followed the migration surge, especially between 1992 to 2004, and different unbuilt land covers have been converted to built-up areas [64]. The expansion of built-up areas generated an uncontrolled increase in an impermeable surface area [80] that can increase the likelihood of flooding, particularly when there is heavy precipitation. Since the level of resilience in urban communities is intrinsically linked to the interaction of the hazard event characteristics and the antecedent conditions, measuring resilience can lead to better understanding of the potential performance of districts in the time of an adverse event.

Table 2
Summary table of flood events in Tehran; Sources [62,63].

Year	Death	Injured-missing	Houses destroyed and damaged	Economic losses (1000$)
1954	2150	–	–	–
1955–1986	118	40	–	10,700
1987	1010	1027	862	7.655,000
1988	146	106	100	150, 000
1989–2010	39	65	348	38,000
2012	8	7	–	21, 000
2015	11	22	–	–

3. Results and discussion

3.1. Selection of a conceptual framework and identification of valid indicators

Cities are complex systems comprising many interacting subsystems. In the meantime, resilience as a dynamic process necessitates focusing on both the inherent robustness and the adaptive capacities of the community. Therefore, an approach that views resilience as a dynamic process and can assist to measure the baselines for assets and capacities is needed to help cities to deal with unexpected shocks or stresses. As highlighted in the previous section, the BRIC was selected as the conceptual framework for this study. This is due to the fact that this approach can provide an empirically index-based resilience metric for assessing the present-day level of resilience by considering both the characteristics and capacities of the place within six major dimensions (social, economic, institutional, infrastructural, community capital and environmental resilience).

For the transition from conceptual framework to empirical assessment, measurable individual indicators were determined based on the mentioned metrics in section 2.2. After collecting the data, the indicator sets with 33 individual indicators were deemed fitting to be combined to create an index for disaster resilience in the study area. Fig. 4 illustrates the indicator sets with the description of calculation for the individual indicators as well as the corresponding justifications and their effect on resilience. In this study, social resilience dimension includes seven individual indicators that analyze the context-related capacities of different population groups within urban districts that can effectively respond in time of flooding. The seven individual indicators in economic dimension measure redundancy, and resourcefulness of the community economy as well as the performance of urban districts at the time of disturbances and recover from the shock to achieve the desired state [81].

Although one aspect of institutional resilience can refer to the attributes connected with e.g. mitigation planning, prior disaster experience and organizational fragmentation [31,82], another aspect can be represented by other variables such as population stability (dynamic factor) that indirectly put strong pressures on institutions (more static nature) [15,82]. In this regard, two indicators including population change and construction boom were considered for this dimension. These indicators were seen as causes for institutions’ inability to rapidly adjust to external pressures and transform in the context of urban development with high construction rate [43].

Infrastructural resilience is characterized as community response and recovery capacity, as well as the number of assets that may be susceptible to flood hazards [15,31,49]. The nine individual indicators in this dimension capture the quality and functionality of critical infrastructures ability to perform before, during, and after of an adverse event in an efficient and timely manner. In the community capital dimension, the four indicators indicate the degree of the linkage between individuals and their larger neighborhoods [15,31]. These metrics such as the number of civic organizations can demonstrate the capacity of

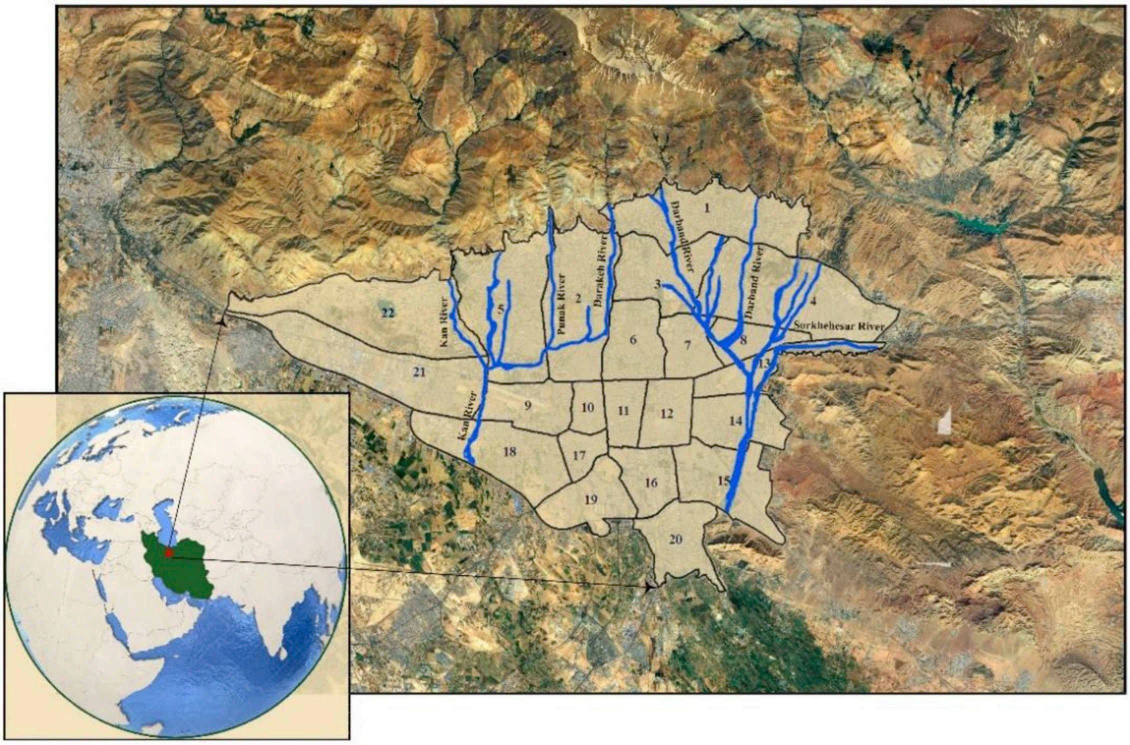

Fig. 3. The 22 urban districts of Tehran and the position of major rivers ("Atlas of Tehran," 2016).

communities to create resilience culture, cope with and recover from the effects of disturbances. Finally, the four individual indicators in environmental dimension refer to qualities of the urban environment that can increase or reduce the flooding risk. For instance, the figure-ground diagram (the relationship between built and unbuilt urban space) can show the ratio of impermeable to permeable surfaces. Similarly, urban growth rate indicates the ratio of land-cover change that has a direct repercussion on the level of flood resilience. The districts that have river valleys have also a different level of flood resilience because they are likely to be more exposed to floods [9,83].

3.2. Multivariate analysis and data reduction

"When starting with a large number of candidate indicators, it is desirable to reduce the pool by identifying the most significant indicators, removing indicators of low relevance, and minimizing the redundancy of highly correlated variables" [24]. In order to eliminate indicators with high correlation, the mentioned prioritized strategies in section 2.3 were followed. In total, 11 indicators were eliminated from further analysis. These indicators were RMW, TEL, CAR, FLF, INT, SCH, CME, URB, PLA, HAG and LRS.

3.3. Using hybrid AHP-TOPSIS method for weighting the indicators and ranking the urban districts

Firstly, the AHP method was performed to obtain the experts' opinions on the relative importance of individual indicators for flood resilience (see section 2.4). We selected experts with an in-depth knowledge of flood risk management in Tehran, in order to be able to conduct weighting based on expert opinion. Afterward, we calculated the average weights given by the five experts as the final weights of each indicator. As Fig. 5 presents, indicators of environmental and infrastructural dimensions have the highest importance. This shows the level of contribution by these two dimensions to the flood resilience of districts. In details, the four highest weights are associated with FGD, HBD, RIV, and EVC; by contrast, the four lowest weights belong to REC, DIS, RLG, and EDU.

Secondly, after assigning weight to each individual indicator, the TOPSIS technique was utilized (see Appendix A and B) to evaluate the resilience level of districts comparatively. Since TOPSIS is based on distance, it is assumed that there is an ideal and non-ideal solution. Therefore, the district with the highest level of resilience has the shortest distance to the positive ideal solution (S^+) and the farthest distance to the ideal negative solution (S^-). Fig. 6 depicts the distance of each district from S^+ and S^- in the six resilience dimensions as well as the overall resilience. For example, District 1 and 2 (D1 and D2) have the farthest distance from S^- and the shortest distance from S^+ in social resilience. This means that these two districts have the highest level of social resilience. Conversely, in environmental resilience, D1 has the farthest distance from S^+ and the shortest distance from S^- that makes the district the least resilient in this dimension. In the same way, in overall disaster resilience, the separation of each district from the ideal and non-ideal solutions can be seen in Fig. 6, by this means, D1 and D6 as the least and the most resilience areas are distinguishable.

Lastly, the relative closeness (C_i) to the positive ideal solution was calculated to indicate the final scores of the urban districts and their ranking based on their resilience level. Table 3 illustrates the final obtained results from the AHP-TOPSIS hybrid process for the six resilience dimensions.

Fig. 7 demonstrates the ranking of the districts' flood resilience in descending order. The results clarify that D6 and D22 are comparatively the most resilient districts within the study area. According to Table 3, D6 ranks well in all dimensions except the institutional dimension. This is because of e.g. the high level of education equality, the high percentage of the independent population, access to the public recreational facilities, employment rate, commercial establishments and infrastructure, access to emergency services and medical care and low percent of worn-out texture to name a few. The underlying deriving factors

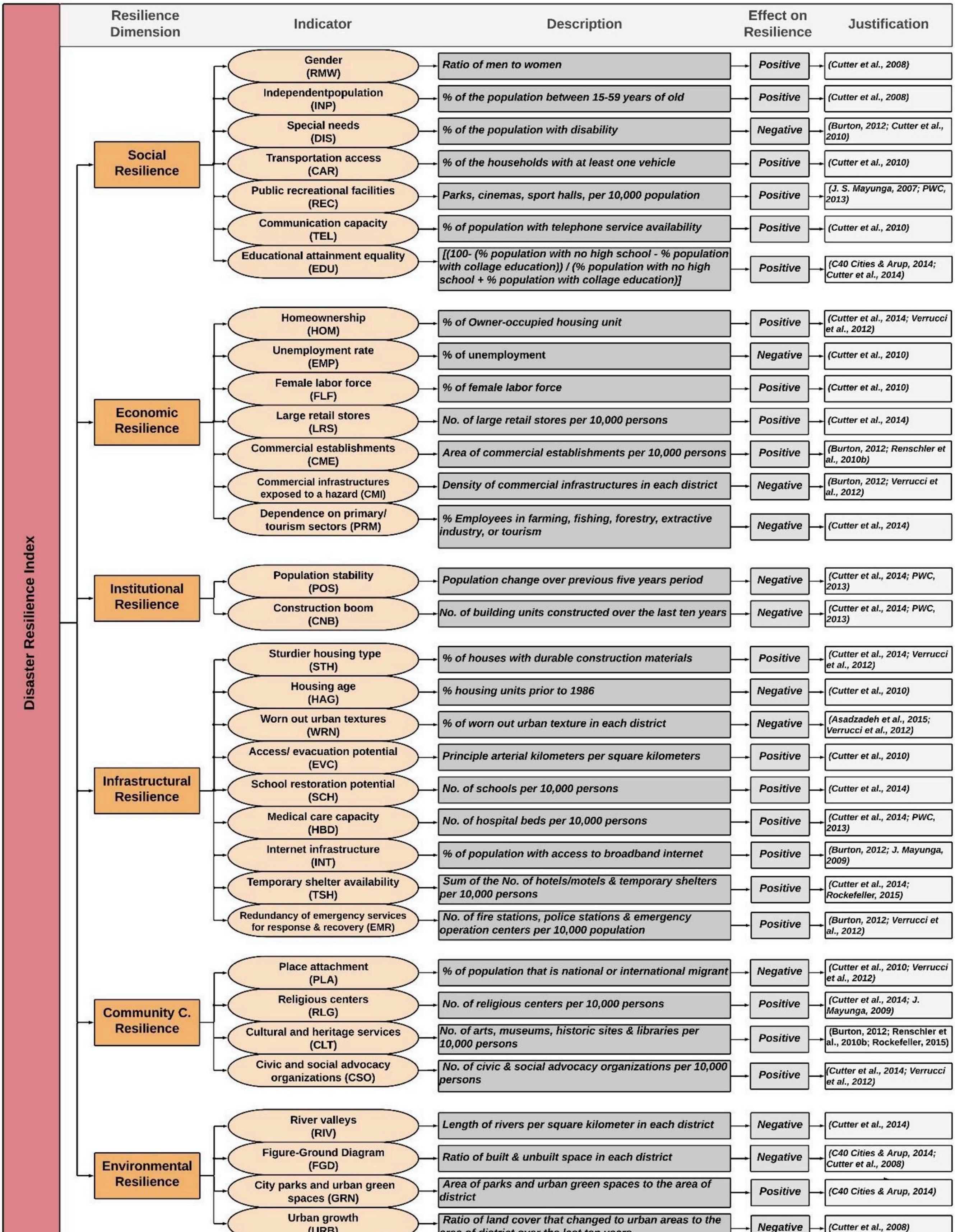

Fig. 4. Candidate set of indicators for six disaster resilience dimensions; (compiled from different sources).

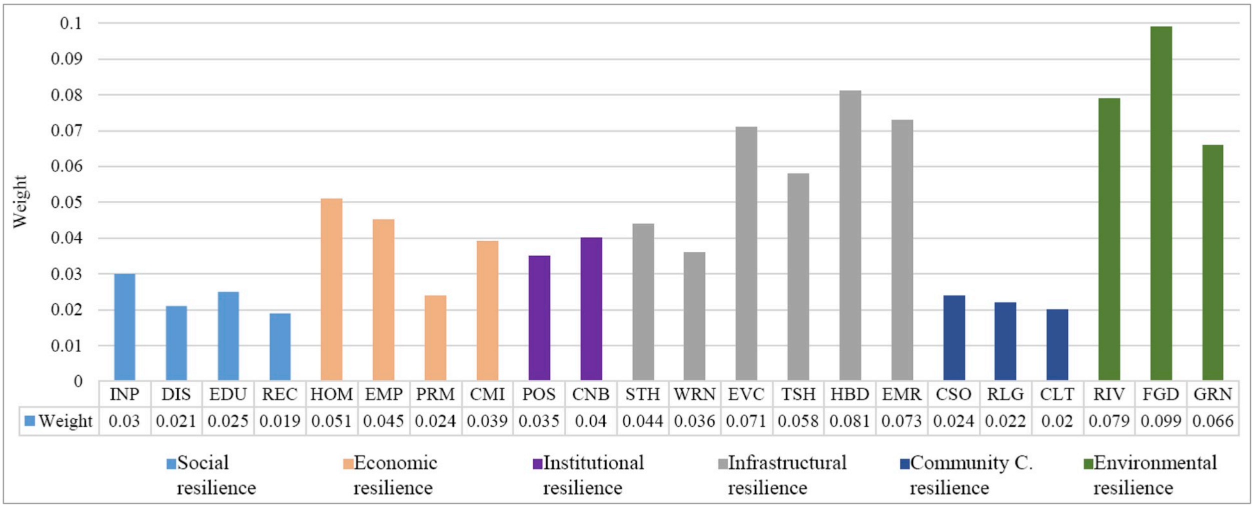

Fig. 5. Final individual indicators' weight obtained from the AHP.

that contribute to this outcome for D22 are institutional, infrastructural and social features. For instance, since this district has had the latest urban development planning, the infrastructure is planned in a more resilient way and there is a good level of infrastructural adequacy in this part of the city. Moreover, the population is more stable since it avoided the construction boom and institutions adjusted successfully to external pressures. Surprisingly, D1 is ranking as the poorest district in terms of flood resilience. Although it has a high level of social resilience, this result is the consequence of the environmental and institutional characteristics. In D1, the ratio of built-up area to unbuilt area is very high resulting in extensive and impermeable surfaces. Thus, in case of a flood, the runoff cannot be absorbed by the surface and the water flow can be intensified. To compound this issue, one of the main rivers of Tehran is located in this district, which results in more exposure to floods. The results are visualized in the next section in order to see the geographic pattern of flood resilience in Tehran.

3.4. Mapping the DRI scores

In this section, the obtained results were mapped in order to better understand the comparative levels of resilience in the six dimensions of flood resilience as well as the spatial distribution of DRI for 22 urban districts in Tehran. To perform this task, the standard deviation from the mean (Z-scores) were used to classify the districts' level of resilience under five classes. The districts with a score greater than 1.5 were considered as high resilience and visualized as dark green. Similarly, the districts with the score between 0.5 to 1.5 were classified as relatively high resilience (light green), between -0.5 to 0.5 as moderate resilience (smoky white), between -1.5 to -0.5 as relatively low resilience (light purple) and finally, the districts with the score of less than -1.5 were classified as low resilience (dark purple).

According to Fig. 8, social resilience has an evident spatial pattern in which the resilience level has gradually been decreased from the northern regions to the southern part. A possible explanation for this may be the higher quality of life in northern regions, which are the more affluent districts of Tehran. This indicates that the city bears the burden of inequitable distribution of basic urban facilities and services. It also highlights the strong need to embrace principles of the equitable development process and social well-being with a focus on the designing of guidelines for providing fair access to critical resources as well as enhancing the capacities of the population to mitigate disasters and adapt to them [84,85]. In the economic resilience component, the center of the city has a higher level of resilience. This is due to the concentration of commercial properties and a large number of regional retail stores. Institutional dimension displays that most districts have moderate resilience. However, the western part of the city is markedly in a better situation. This is because these regions have gradually been developed, thus the institutions have been able to adapt to the impacts of population growth and construction boom. Surprisingly, none of the districts ranked low in infrastructural resilience. Most of the districts display a moderate level of infrastructural resilience as one of the significant factors in city resilience. Hence, this result reveals the need for enhanced physical infrastructure in the city. In contrast to social resilience, there is no clear spatial pattern in community capital resilience. Moreover, most districts are classified from moderate to low resilience in this dimension, which explains that the linkage between the individuals and their neighborhood is weak. The environmental resilience demonstrates that the northern, central and eastern quarters are more susceptible to floods whereas, high and relatively high environmental resilience found in the southern part of the city. This can be related to the location of the rivers within the city, as well as the area of permeable land covers.

Finally, the comparative overview of flood resilience in Tehran indicates that D1 is the only district with the lowest level of resilience. In this district, all resilience dimensions are moderate and low resilience, except social resilience. On the other hand, D6 and D22 are ranked as high in flood resilience. All resilience sub-components are high and relatively high in both districts, excluding economic resilience for D22 and environmental resilience for D6. According to the spatial pattern of flood resilience, 15 districts are clustered as relatively low and moderate resilience and only four districts are categorized as relatively high resilience. The achieved results provide a better overview of resilience levels at the city scale and highlight where the interventions are needed more.

3.5. Validation of empirical results

In order to understand to what extent the hybrid AHP-TOPSIS method and the calculated resilience scores are trustable, cross-validation for empirical results was conducted. In this regard, since we applied the BRIC approach with its structure and methodology on the same datasets in our previous study [86], the obtained results from these two different methods were compared. After investigating their possible relationship using Pearson's correlation coefficient, a value of 0.79 (statistically significant at the 0.01 level) were calculated. This reveals that both methodologies address the same underlying

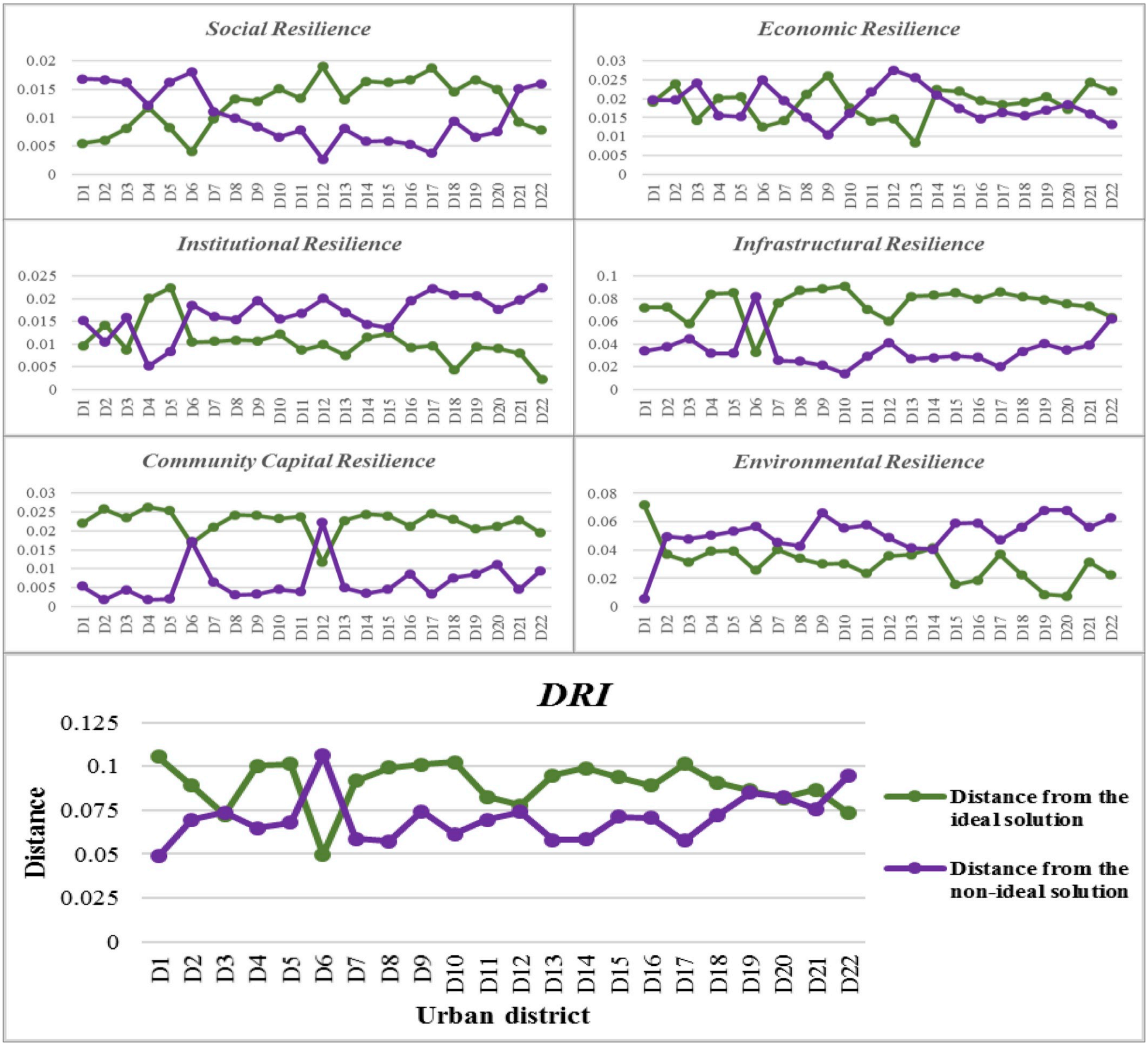

Fig. 6. The separation of each urban district from the positive and negative ideal solutions.

phenomena and validates the empirical results obtained from the hybrid approach. Fig. 9 represents the relative resilience score and of urban districts obtained from the AHP-TOPSIS versus the BRIC approach.

3.6. Limitations and future research

First, Although composite indicator building has often been employed to operationalize the concept of community disaster resilience in existing literature [25], data availability and accessibility for the identified individual indicators are a common limitation in this approach. Consequently, some of the variables should be eliminated because of unavailability or inaccessibility and this might affect the obtained results of the study. For example in this study, institutional resilience, which has an important role in preparedness and planning phase for disaster resilience, is quantified just by two variables due to this constraint. Next, AHP has a limitation when dealing with interdependence criteria because it assumes they are independent [87]. Moreover, only a limited number of variables can be considered using pairwise comparison since it is cognitively demanding [88], albeit it was found an easy method for eliciting of criteria weight by the experts in this study. Therefore, this should be considered for future studies. However, MCDM methods help to capture experts' opinion and involve stockholders with different backgrounds, a sensitivity analysis is needed to conduct in such studies to check the stability of results and increase the credibility of the decisions [57]. This analysis can be done for future research. Last, since the validation of disaster resilience studies is often problematic due to the absence of information regarding the recorded impacts of the past natural disasters, the validation based on actual flood outcomes in Tehran was not possible. In addition, the timeline of the study plays an important role for a robust validation because there would be considerable changes specifically in land uses and land covers

Table 3
Resilience scores and the ranking of districts in the six resilience dimensions.

Urban District	Social Resilience	Rank	Economic Resilience	Rank	Institutional Resilience	Rank	Infrastructural Resilience	Rank	Community C. Resilience	Rank	Environmental Resilience	Rank
D1	0.753	2	0.507	8	0.613	14	0.319	8	0.198	9	0.073	22
D2	0.735	3	0.451	13	0.424	20	0.339	6	0.064	22	0.573	15
D3	0.668	5	0.627	4	0.643	12	0.437	3	0.157	14	0.602	12
D4	0.508	9	0.436	16	0.204	22	0.274	12	0.064	21	0.563	16
D5	0.66	6	0.425	18	0.272	21	0.273	13	0.074	20	0.573	14
D6	0.816	1	0.665	2	0.641	13	0.715	1	0.509	2	0.688	8
D7	0.530	8	0.577	6	0.601	15	0.252	17	0.236	8	0.529	20
D8	0.427	10	0.415	19	0.586	16	0.222	19	0.113	19	0.558	18
D9	0.395	11	0.287	22	0.647	11	0.194	20	0.122	17	0.686	9
D10	0.304	16	0.479	10	0.559	17	0.133	22	0.161	12	0.644	10
D11	0.368	14	0.606	5	0.659	10	0.290	11	0.140	15	0.710	7
D12	0.124	22	0.652	3	0.670	8	0.407	4	0.654	1	0.576	13
D13	0.382	13	0.754	1	0.693	5	0.248	18	0.181	10	0.529	19
D14	0.259	19	0.483	9	0.555	18	0.252	16	0.126	16	0.494	21
D15	0.266	18	0.442	15	0.522	19	0.256	15	0.157	13	0.790	3
D16	0.242	20	0.430	17	0.679	7	0.262	14	0.288	6	0.759	4
D17	0.164	21	0.470	11	0.698	4	0.189	21	0.119	18	0.560	17
D18	0.392	12	0.448	14	0.829	2	0.291	10	0.248	7	0.716	6
D19	0.282	17	0.451	12	0.687	6	0.337	7	0.294	5	0.889	2
D20	0.334	15	0.518	7	0.662	9	0.316	9	0.346	3	0.902	1
D21	0.621	7	0.397	20	0.71	3	0.346	5	0.162	11	0.638	11
D22	0.672	4	0.372	21	0.908	1	0.495	2	0.326	4	0.737	5

in between the two dates of the study and the recorded actual data or even another study [89].

4. Conclusions

Measuring urban resilience can contribute to the development of appropriate strategies and policies for cities facing unexpected shocks and their consequences. The measurement of urban disaster resilience is important for Tehran due to its inherent characteristics and the spatial-temporal variations of floods over the region. Furthermore, in the absence of flood-oriented studies, this study aimed to increase our understanding of the factors and processes of urban flood resilience in Tehran. To perform this task, we developed a composite index that consists of six fundamental steps.

By using the BRIC, we identified a sound set of 33 indicators in order to quantify the multifaceted concept of urban flood resilience that includes the six fundamental dimensions (social, economic, institutional, and infrastructural, community capital and environmental resilience). While the developed methodology presents a clear guideline to operationalize the concept of resilience, it underlines the individual indicators weighting and resilience ranking using the AHP-TOPSIS hybrid method. This hybrid approach provides a tool to integrate qualitative assessment into quantities analysis. In developing a place-based assessment of disaster resilience, each indicator would have a different impact on resilience level. Since there has been a considerable knowledge about the relative importance of the indicators, a knowledge-driven approach was performed to assign unequal importance across them. So that, firstly, using the AHP technique predisposed us to integrate the knowledge of local experts into the analysis and obtain the trade-offs among indicators after synthesizing the experts' judgments. Secondly, in the absence of an absolute standard for measuring resilience level, the TOPSIS assumes that the ideal urban district has the best level for all attributes. In other words, the technique aims at comparatively ranking the urban districts based on the shortest distance to the ideal solution and the farthest distance to the non-ideal solution.

Mapping of the obtained results illustrated the distinct spatial

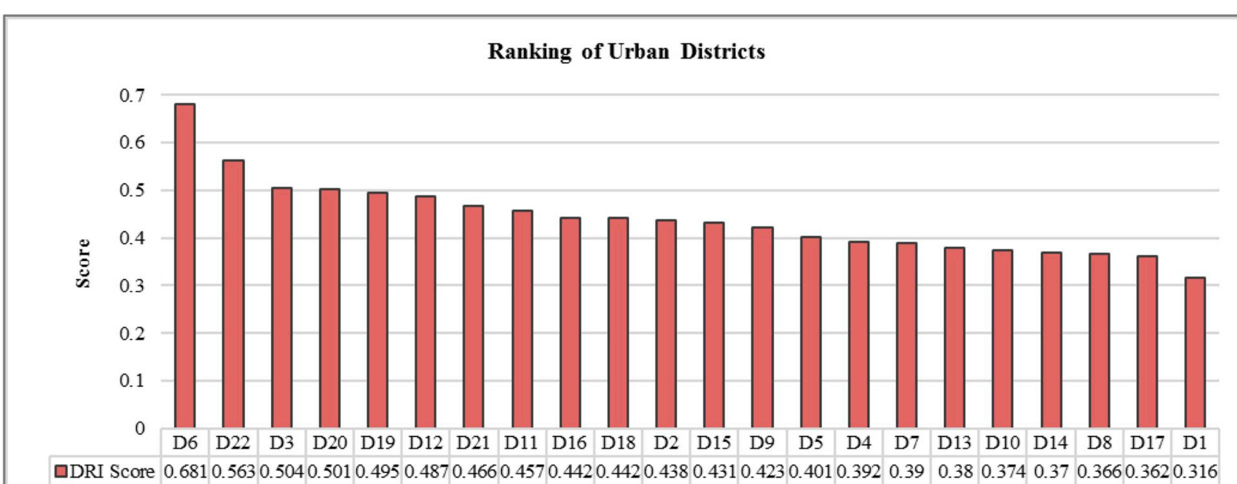

Fig. 7. DRI scores for the 22 urban districts and their ranking.

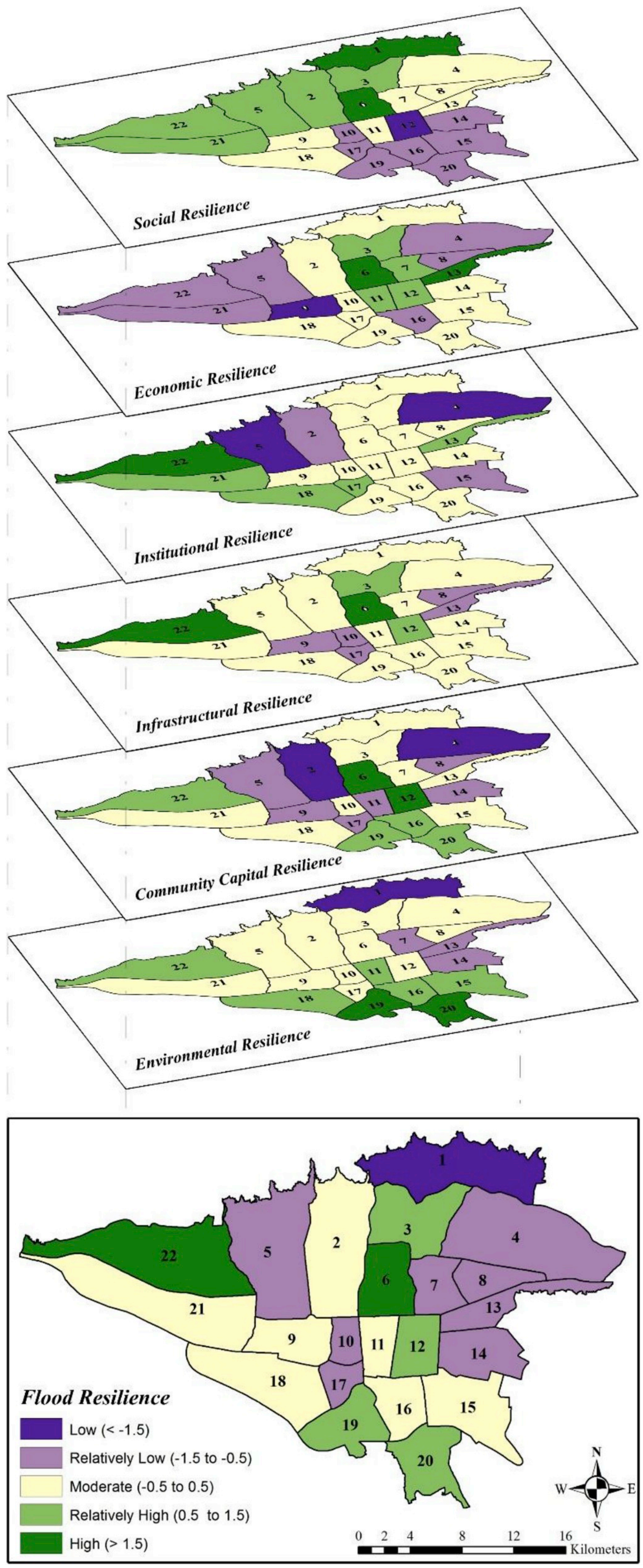

Fig. 8. Disaster resilience index for 22 Tehran urban districts along with its six dimensions.

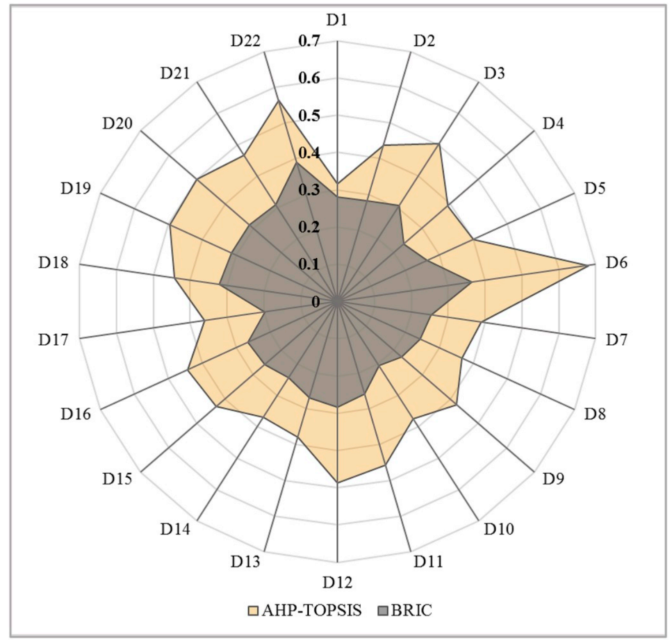

Fig. 9. The scores of DRI using the hybrids AHP-TOPSIS and BRIC approaches.

patterns of the drivers of resilience and identified the hot-spots of flood resilience in the study area that need more interventions. For instance, the eastern and northeastern districts are less resilient and therefore, need more attention. The underlying factors are mostly environmental and infrastructural attributes, which are directly related to the land-use and infrastructural planning. Using an internal validation (comparing the findings of AHP-TOPSIS and BRIC models) helped to understand that the obtained results by the proposed method are trustable and can be utilized by local stakeholders and end-users. For instance, the findings can contribute to urban planning organizations such as Tehran Research Planning Center to integrate disaster resilience into urban planning, and shift from reactive plans to proactive urban adaptive strategies such as risk-sensitive urban land-use planning. The findings also help to identify the possible hotspots of the city that can be considered by emergency management institutions, e.g. Tehran Disaster Mitigation Organization for effective disaster risk management.

Among the maps of resilience dimensions, social resilience has a distinctive pattern. It shows a gradual decrease in social resilience level from the north to the south of the city. Social resilience is a fundamental necessity in building capacity for communities and individuals to prepare for, respond to, recover from and adapt to the impacts of climate change. Thus, the local stockholders can take this into consideration in order to promote equitable development process and provide fair access to critical urban resources.

However, developing composite indicators and measuring resilience was associated with some challenges in this study. The most significant referred to the accessibility and quality of data in general and, in particular, for institutional dimension. Another challenge was the absence of a systematic approach to document the adverse impacts caused by flood events as well as the lack of flood-oriented studies in Tehran for the validation step.

In a nutshell, performing an index-based resilience measurement is conducted to enhance our understanding of what contributes to the flood resilience in Tehran. This helps to outline areas that need more intervention in terms of disaster risk-informed urban planning and management. This can guide decision makers prioritize projects that advance resilient communities. However, the question of whether such measurements can adequately address the ongoing or emerging needs of local stakeholders and planning practitioners highlights the need for focusing on more bottom-up and participatory measurements in order to achieve a shared vision and common missions.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101069.

Appendix A. Normalized decision matrix in TOPSIS method for the 22 resilience indicators in the 22 urban districts of Tehran

Weight	0.03	0.021	0.025	0.019	0.051	0.045	0.024	0.039	0.035	0.04	0.044	0.036	0.071	0.058	0.081	0.073	0.024	0.022	0.02	0.079	0.099	0.066
Effect on resilience	+	–	+	+	+	–	+	–	–	–	+	–	+	+	+	+	+	+	+	–	–	+
	INP	DIS	EDU	REC	HOM	EMP	PRM	CMI	POS	CNB	STH	WRN	EVC	TSH	HBD	EMR	CSO	RLG	CLT	RIV	FGD	GRN
D1	0.895	0.223	0.902	0.474	0.793	0.397	0.364	0.052	0.229	0.417	0.837	0.026	0.018	0.286	0.245	0.212	0.231	0.217	0.153	1	1	0.191
D2	0.947	0.149	0.789	0.418	0.987	0.926	0.318	0.133	0.641	0.562	0.873	0.008	0.721	0.124	0.218	0.145	0.093	0.066	0.014	0.892	0.209	0.721
D3	0.491	0	0.986	0.388	1	0.412	0	0.474	0.487	0.326	0.86	0.015	0.248	0.571	0.381	0.326	0.241	0.118	0.062	0.617	0.221	0.43
D4	0.649	0.135	0.413	0.033	0.393	0.397	0.818	0.17	0.612	0.855	0.697	0.002	0.652	0.033	0.055	0.068	0	0.143	0.015	0.888	0.128	0.39
D5	0.965	0.053	0.649	0.21	0.62	0.559	0.227	0.152	0.191	1	1	0.004	0.534	0.042	0.021	0.097	0.063	0.125	0.043	0.95	0.093	0.501
D6	0.789	0.095	1	0.66	0.927	0.544	0.227	0.836	0.937	0.167	0.75	0.004	0.378	1	1	0.422	1	0.165	0.264	0	0.279	0.327
D7	0.526	0.378	0.483	0.507	0.533	0.426	0.545	0.647	0.809	0.289	0.387	0.293	0.268	0.146	0.243	0.081	0.281	0.262	0.174	0.04	0.523	0.077
D8	0.509	0.285	0.345	0	0.553	0.529	0.591	0.079	0.809	0.312	0.5	0.206	0.512	0.077	0.003	0.063	0.087	0.13	0.125	0.258	0.453	0.326
D9	0.351	0.449	0.291	0.422	0	0.632	0.727	0.311	1	0.119	0.083	0.142	0.131	0	0.025	0.13	0.11	0.181	0.093	0.089	0	0
D10	0.368	0.53	0.175	0.123	0.38	0.515	0.591	0.576	0.981	0.304	0.437	1	0.427	0.003	0.047	0	0.19	0.234	0.069	0	0.291	0.142
D11	0.421	0.563	0.361	0.193	0.367	0.265	0.636	0.812	0.603	0.27	0.613	0.552	0	0.394	0.235	0.307	0.136	0.231	0.07	0	0.256	0.381
D12	0.018	1	0.211	0.143	0.253	0	1	1	0.932	0.098	0.36	0.699	0.044	0.627	0.336	0.541	0.293	1	1	0	0.465	0.178
D13	0.386	0.629	0.261	0.549	0.773	0.162	0.682	0.663	0.338	0.299	0.57	0.081	0.397	0.092	0.072	0.14	0.131	0.079	0.252	0.455	0.372	0.177
D14	0.105	0.494	0.139	0.237	0.271	0.029	0.955	0	0.795	0.361	0.48	0.202	0.656	0.068	0.049	0.125	0.192	0	0.086	0.126	0.616	0.262
D15	0.281	0.55	0.042	0.233	0.2	0.221	0.955	0.143	0.839	0.396	0.157	0.149	0.751	0.087	0.014	0.101	0.236	0.175	0.007	0.203	0.198	0.745
D16	0.123	0.665	0.082	0.421	0.333	0.603	0.682	0.539	0.852	0.123	0	0.17	0.441	0.202	0.043	0.309	0.214	0.612	0.086	0	0.314	0.789
D17	0	0.639	0.075	0.057	0.28	0.485	0.545	0.638	0.929	0	0.003	0.552	0.556	0.109	0.016	0.136	0.193	0.044	0.044	0	0.535	0.289
D18	0.298	0.16	0.075	0.319	0.36	0.441	0.773	0.344	0	0.192	0.39	0.051	0.843	0.101	0.067	0.101	0.169	0.561	0	0.111	0.233	0.417
D19	0.105	0.561	0	0.532	0.193	0.265	0.818	0.309	0.897	0.07	0.69	0.021	1	0.204	0	0.283	0.47	0.231	0.106	0	0.151	1
D20	0.211	0.427	0.098	0.469	0.44	0.221	0.409	0.322	0.738	0.215	0.44	0.115	0.669	0.258	0.048	0.366	0.176	0.852	0.085	0.045	0.07	0.8
D21	1	0.363	0.261	0.788	0.727	1	0.818	0.213	0.727	0.126	0.653	0.002	0.652	0.273	0.049	0.443	0.152	0.226	0.132	0.11	0.209	0.031
D22	0.789	0.112	0.35	1	0.187	0.5	0.727	0.328	0.137	0.079	0.897	0	0.607	0.71	0.061	1	0.487	0.359	0.112	0.241	0.023	0.321

Appendix B. Weighted normalized decision matrix in TOPSIS method for the 22 resilience indicators in the 22 urban districts of Tehran

	INP	DIS	EDUC	REC	HOM	EMP	PRM	CMI	POS	CNB	STH
D1	0.0102	0.0022	0.0101	0.0043	0.0156	0.0077	0.0028	0.0009	0.0024	0.0093	0.013
D2	0.0108	0.0015	0.0089	0.0038	0.0194	0.018	0.0025	0.0023	0.0066	0.0125	0.0136
D3	0.0056	0	0.0111	0.0035	0.0196	0.008	0	0.0082	0.005	0.0073	0.0134
D4	0.0074	0.0013	0.0046	0.0003	0.0077	0.0077	0.0063	0.0029	0.0063	0.019	0.0109
D5	0.011	0.0005	0.0073	0.0019	0.0122	0.0108	0.0018	0.0026	0.002	0.0223	0.0156
D6	0.009	0.0009	0.0112	0.006	0.0182	0.0105	0.0018	0.0144	0.0097	0.0037	0.0117
D7	0.006	0.0037	0.0054	0.0046	0.0105	0.0083	0.0042	0.0111	0.0084	0.0064	0.006
D8	0.0058	0.0028	0.0039	0	0.0108	0.0103	0.0046	0.0014	0.0084	0.0069	0.0078
D9	0.004	0.0044	0.0033	0.0038	0	0.0123	0.0056	0.0054	0.0104	0.0026	0.0013
D10	0.0042	0.0052	0.002	0.0011	0.0075	0.01	0.0046	0.0099	0.0102	0.0068	0.0068
D11	0.0048	0.0055	0.0041	0.0018	0.0072	0.0051	0.0049	0.014	0.0062	0.006	0.0095
D12	0.0002	0.0098	0.0024	0.0013	0.005	0	0.0077	0.0172	0.0096	0.0022	0.0056
D13	0.0044	0.0062	0.0029	0.005	0.0152	0.0031	0.0053	0.0114	0.0035	0.0067	0.0089
D14	0.0012	0.0048	0.0016	0.0022	0.0053	0.0006	0.0074	0	0.0082	0.008	0.0075
D15	0.0032	0.0054	0.0005	0.0021	0.0039	0.0043	0.0074	0.0025	0.0087	0.0088	0.0024
D16	0.0014	0.0065	0.0009	0.0038	0.0065	0.0117	0.0053	0.0093	0.0088	0.0027	0
D17	0	0.0063	0.0008	0.0005	0.0055	0.0094	0.0042	0.011	0.0096	0	0
D18	0.0034	0.0016	0.0008	0.0029	0.0071	0.0086	0.006	0.0059	0	0.0043	0.0061
D19	0.0012	0.0055	0	0.0048	0.0038	0.0051	0.0063	0.0053	0.0093	0.0016	0.0107
D20	0.0024	0.0042	0.0011	0.0043	0.0086	0.0043	0.0032	0.0055	0.0076	0.0048	0.0069
D21	0.0114	0.0036	0.0029	0.0072	0.0143	0.0194	0.0063	0.0037	0.0075	0.0028	0.0102
D22	0.009	0.0011	0.0039	0.0091	0.0037	0.0097	0.0056	0.0056	0.0014	0.0018	0.014

	WRN	EVC	TSH	HBD	EMR	CSO	RLG	CLT	RIV	FGD	GRN
D1	0.0006	0.0005	0.01	0.0162	0.0101	0.0038	0.0027	0.0027	0.0381	0.0562	0.0057
D2	0.0002	0.02	0.0043	0.0144	0.0069	0.0015	0.0008	0.0002	0.034	0.0117	0.0216
D3	0.0004	0.0069	0.0199	0.0251	0.0155	0.004	0.0015	0.0011	0.0235	0.0124	0.0129
D4	0	0.018	0.0011	0.0036	0.0032	0	0.0018	0.0003	0.0339	0.0072	0.0117
D5	0.0001	0.0148	0.0015	0.0014	0.0046	0.001	0.0016	0.0008	0.0362	0.0052	0.015
D6	0.0001	0.0105	0.0348	0.0659	0.0201	0.0166	0.0021	0.0046	0	0.0157	0.0098
D7	0.0069	0.0074	0.0051	0.016	0.0039	0.0047	0.0033	0.0031	0.0015	0.0294	0.0023
D8	0.0048	0.0142	0.0027	0.0002	0.003	0.0014	0.0016	0.0022	0.0098	0.0254	0.0098
D9	0.0033	0.0036	0	0.0016	0.0062	0.0018	0.0023	0.0016	0.0034	0	0
D10	0.0234	0.0118	0.0001	0.0031	0	0.0031	0.003	0.0012	0	0.0163	0.0043
D11	0.0129	0	0.0137	0.0155	0.0146	0.0023	0.0029	0.0012	0	0.0144	0.0114

D12	0.0164	0.0012	0.0218	0.0222	0.0257	0.0049	0.0126	0.0176	0	0.0261	0.0053
D13	0.0019	0.011	0.0032	0.0047	0.0067	0.0022	0.001	0.0044	0.0174	0.0209	0.0053
D14	0.0047	0.0182	0.0024	0.0032	0.0059	0.0032	0	0.0015	0.0048	0.0346	0.0079
D15	0.0035	0.0208	0.003	0.0009	0.0048	0.0039	0.0022	0.0001	0.0077	0.0111	0.0224
D16	0.004	0.0122	0.007	0.0028	0.0147	0.0035	0.0077	0.0015	0	0.0176	0.0237
D17	0.0129	0.0154	0.0038	0.0011	0.0065	0.0032	0.0006	0.0008	0	0.03	0.0087
D18	0.0012	0.0233	0.0035	0.0044	0.0048	0.0028	0.0071	0	0.0042	0.0131	0.0125
D19	0.0005	0.0277	0.0071	0	0.0135	0.0078	0.0029	0.0019	0	0.0085	0.03
D20	0.0027	0.0185	0.009	0.0032	0.0174	0.0029	0.0107	0.0015	0.0017	0.0039	0.024
D21	0	0.018	0.0095	0.0032	0.0211	0.0025	0.0029	0.0023	0.0042	0.0117	0.0009
D22	0	0.0168	0.0247	0.004	0.0475	0.0081	0.0045	0.002	0.0092	0.0013	0.0096

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CHAPTER 4

DEVELOPMENT OF A FRAMEWORK FOR UTILIZING CROWDSOURCING AND VGI TOWARD TRANSFORMATIVE DISASTER RESILIENCE

This chapter begins with the argument that it is necessary to address the concept of transformative resilience when and where conventional and top-down resilience initiatives are likely to deliver less effective strategies, plans, and actionable measures in light of the fact that new crises of an unpredictable nature, such as extreme floods and pandemics, are likely to occur more frequently. Transformative resilience pathways emphasize the importance of reflexive governance, inclusive co-creation of knowledge, innovative and collaborative learning, and self-organizing processes. To support these transformative pathways, the use of new data sources (e.g., crowdsourcing and VGI) and innovative cutting-edge techniques (e.g., machine learning) are being promoted to mobilize the creativity and engagement needed to address these crises. However, there is a lack of comprehensive understanding of the complexities and opportunities of using crowdsourcing and VGI for transformative resilience. Therefore, based on a qualitative content analysis of available resources, this chapter secondly explores the key aspects of using VGI for transformative resilience and proposes a comprehensive framework structured around the identified legal, institutional, social, economic, and technical aspects to formalize the process of adopting VGI in transformative resilience initiatives.

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A Framework for Scaling Urban Transformative Resilience through Utilizing Volunteered Geographic Information

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Abstract: Resilience in the urban context can be described as a continuum of absorptive, adaptive, and transformative capacities. The need to move toward a sustainable future and bounce forward after any disruption has led recent urban resilience initiatives to engage with the concept of transformative resilience when and where conventional and top-down resilience initiatives are less likely to deliver effective strategies, plans, and implementable actions. Transformative resilience pathways emphasize the importance of reflexive governance, inclusive co-creation of knowledge, innovative and collaborative learning, and self-organizing processes. To support these transformative pathways, considering techno-social co-evolution and digital transformation, using new data sources such as Volunteered Geographic Information (VGI) and crowdsourcing are being promoted. However, a literature review on VGI and transformative resilience reveals that a comprehensive understanding of the complexities and capacities of utilizing VGI for transformative resilience is lacking. Therefore, based on a qualitative content analysis of available resources, this paper explores the key aspects of using VGI for transformative resilience and proposes a comprehensive framework structured around the identified legal, institutional, social, economic, and technical aspects to formalize the process of adopting VGI in transformative resilience initiatives.

Keywords: disaster resilience; transformation; volunteered geographic information (VGI)

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1. Introduction

Global development agendas such as the 2030 Agenda for Sustainable Development (SDGs), the Sendai Framework, and the New Urban Agenda (NUA), as well as academic circles, have emphasized the importance of strengthening cities' resilience to disasters in light of the growing spectrum of risks stemming from climate change, natural hazards, and, more recently, pandemics [1–5]. However, a greater emphasis on disaster resilience requires a shift in focus from a command-and-control model to a more strategic, participatory, and dialogic model by promoting new and innovative technical and scientific methods through community and stakeholder collaboration processes [6,7].

The importance of building urban resilience by considering the important role of governance, people, and technology to tackle challenges and create solutions in a place-based, integrated, inclusive, risk-aware, and forward-looking manner has compelled recent urban resilience initiatives to focus on the concept of transformative resilience, especially when incremental adaptation and conventional resilience planning are insufficient [5,8–10]. Transformational approaches stress the role of citizen participation, techno-social co-evolution, and reflexive governance processes at supranational, national, and local levels [11–14].

To guide transformations and strengthen community resilience, not only should long-term guiding visions and strategies be outlined to improve qualities such as transparency, self-organization, flexibility, and the active role of citizens [15,16], but also, based on today's problems, the development of policies based on the open exchange and multi-level collaboration using digital technologies and data innovations such as Big Data and citizen-generated data should be promoted [4,17]. It is recommended that in the era of digital and data transformation, countries explore the added value of using other data, such as social sensing, crowdsourcing, and Volunteered Geographic Information (VGI), to improve their data capabilities through near-real-time access to geospatial information, leading to better-informed decisions to enable innovation in geospatial technology, improve the quality and applicability of disaster-related data, overcome institutional barriers, and increase community resilience by connecting people to geospatial information services [4,18–20].

It has been more than a decade since the author of [21] defined VGI as 'the harnessing of tools to create, assemble, and disseminate geographic data provided voluntarily by individuals'. Since then, VGI activities ranging from contributions to online crowdsourced mapping to location-related posts on social media contributions, along with digital transformation, have transformed the process of acquiring or providing geospatial data, largely influencing traditional authoritative systems and creating new forms of public engagement based on voluntary contributions [12,22–25]. VGI attributes, such as its timeliness-reflecting spatial dynamics [26], facilitating multidirectional communication, increasing situational awareness, and enabling collective intelligence, may outperform traditional geospatial datasets [22,27].

Thus, utilizing VGI in disaster resilience initiatives can not only help fill the gap in disaster-related geospatial data by engaging volunteers to co-create, curate, and disseminate free, up-to-date, and near-real-time geospatial information [22,28,29], but also create an opportunity for self-organization within the digital volunteer network and enabling remote citizens and volunteers to effectively and actively contribute to disaster resilience initiatives using their technical, local, and on-site knowledge [30–32]. Moreover, the use of such collaborative data ecosystems can play an important role either in improving the accessibility of geospatial information and related techno-social tools for all or in developing innovative, customized tools that lead to disaster risk reduction and community resilience [18,33].

Against this backdrop, while previous studies have discussed the opportunities and challenges associated with using VGI for disaster resilience, they have notably lacked conceptual framework underpinnings, leaving the overall picture of VGI for urban resilience unclear. Accordingly, this paper aims to address this gap and explore the various aspects of using VGI to facilitate and support transformative resilience. It also proposes a comprehensive framework that structures identified aspects to formalize the process of adopting VGI for transformative disaster resilience. In the remainder of this paper, Section 2 manifests the research background on transformative resilience. Section 3 presents the research methodology used in this study. Sections 4 and 5 discuss in detail the various aspects of using VGI for transformative resilience. Section 6 presents a comprehensive framework for leveraging VGI to facilitate transformative resilience. Finally, the key challenges and limitations associated with VGI-based initiatives, as well as the agenda for future research directions and conclusions, are drawn in Sections 7 and 8, respectively.

2. Transformative Urban Resilience

Resilience in the urban context can be seen as the continuum of (1) the capability of cities and regions to withstand change and bounce back to a previous state (absorptive capacity—short-term), (2) adapt to change and reorganize without altering existing structures (adaptive capacity—medium-term), and (3) transform through learning, self-organization, and exploring new ways along with flexibility and considerable changes in existing structure (transformative capacity—long-term) [9,34–37].

Although embedding a resilience narrative is context-dependent, recent literature on urban resilience questions the effectiveness of existing resilience practices and emphasizes the importance of transformative capacity, rather than relying solely on incremental and absorptive coping capacities [8–10,35]. As new crises of unforeseeable nature, e.g., extreme floods and pandemics, are likely to emerge more frequently, transformation measures can strengthen people and mobilize the creativity and devotion needed for dealing with the crisis [38].

Transformation requires cross-scale awareness and incentives for change and can also improve absorptive and adaptive capacity [39]. Thus, collaborative urban experiments are needed to guide transition pathways by establishing reflexive governance approaches and flexible institutional settings, in which a given problem is jointly perceived and collective visions and missions are developed. In such a setting, resilience strategies are goal-oriented and interactive, policies are legitimized based on collective rationalities, foresight exercises and transdisciplinary research are conducted, and hybrid decision making and planning are employed [9,11,18,34,40,41]. This can lead to enabling collaborative learning and being dynamic to absorb, adapt, transform, and evolve in the face of changes and uncertainties [42–44].

Furthermore, transformative resilience is characterized by system-wide, fundamental, and long-term changes that challenge conventional approaches and aim to deliver innovative, forward-looking, and multiscale approaches based on a common purpose and ensuring new paradigms in thinking, acting, and self-organizing to evolve toward new norms, forms, and functions to achieve sustainability and resilience [9,12,13,34,36,45–47].

The availability and redundancy of resources and services through the use of new data sources (crowdsourcing, open data science, etc.) and the mobilization of cutting-edge technologies, such as the Internet of Things (IoT), Machine Learning (ML), and Digital Twins, to name a few, ensures the creation of backups and the diversification of services and processes through the creation of alternatives based on a system-wide or cross-system perspective, which ultimately contributes to a better urban analysis and informed decision making to improve resilience in the urban context [18,48,49].

Transformative resilience emphasizes the importance of the co-creation of knowledge and collaboration among stakeholders (actors, communities, and citizens), urban systems (housing, transportation, infrastructure, etc.), and institutions before, during, and after a disaster by considering socio-technological acceptability and socioeconomic affordability [10,11]. To scale transformation in resilience governance, planning, and practice, collaboration needs transparency and openness among public institutions, the private sector, and academia. Moreover, to enable meaningful participation, multidirectional communication, and sharing of resilience knowledge, citizen-centric initiatives that include individuals, civic organizations, and relevant communities are required [48,50–54]. These key characteristics of urban resilience that contribute to scaling transformation are detailed in Figure 1.

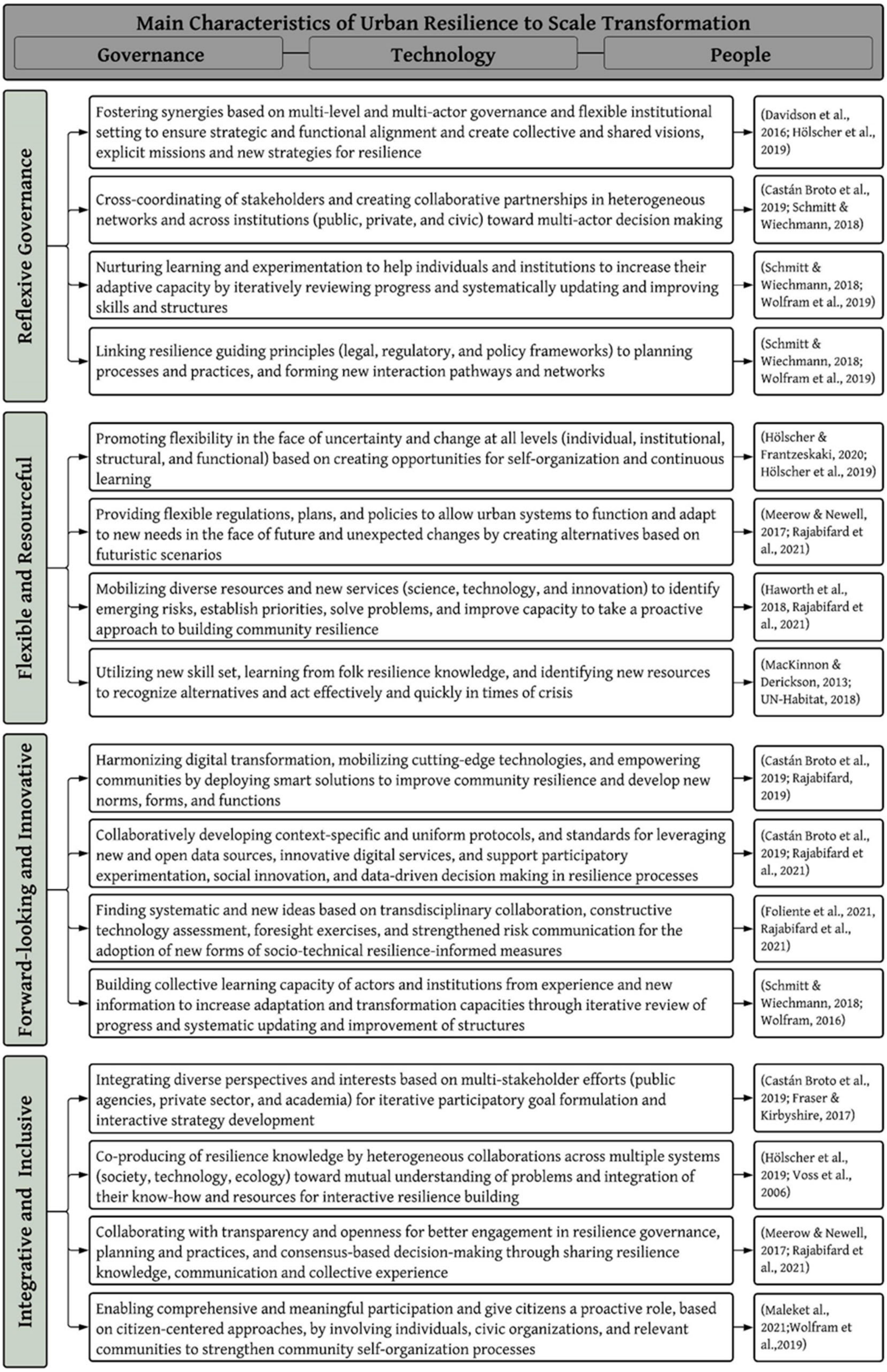

Figure 1. Key characteristics of urban resilience that scale transformation.

3. Research Methodology

As mentioned earlier, the use of VGI for transformative resilience encompasses multiple aspects and involves multidisciplinary bodies of knowledge. Therefore, any attempt to employ VGI toward transformative resilience requires a basic understanding of the VGI aspects in line with the characteristics of transformative resilience. The following main steps were thus taken to establish a conceptual framework. In the first phase, to select our primary studies, we applied the search string ('Volunteered Geographic Information and 'disaster resilience' and 'transformation') to Google Scholar, Web of Science, and Scopus) to search for studies published since 2010, when [55] discussed the topic of VGI for disaster resilience as a frontier area for research, to May 2021. The choice of the search strings was due to our goal of obtaining studies in the field of disaster resilience, and not in other fields applying VGI, such as location-based services for routing and navigating. Studies were selected based on three inclusion criteria: (i) the article matches the keywords, (ii) the article discusses a type of transformation that VGI and crowdsourcing have caused, and (iii) the article discusses the added value and constraints of VGI in disaster resilience. As exclusion criteria, we discarded articles that only mentioned the VGI itself used for the study (e.g., OSM or Tweeter) but did not refer to any aspect of VGI that contributes to the transformative processes in disaster resilience. Excluding conference papers, a total of 82 relevant studies were selected from 414 hits for review. The publications were generally included or excluded by reading the titles and then the abstracts when more detailed decisions had to be made.

The second phase was to identify and extract concepts in the review of previous studies. Therefore, the 'Concept Matrix' method was used as a systematic concept-centric technique for the qualitative and content analysis of available resources to synthesize the literature [56,57]. The concept matrix helps identify opportunities for synthesis that can provide a comprehensive understanding of a topic revealed by overlapping statements in individual sources [58]. To develop the concept matrix, the references were listed in the left column of the matrix, while the title of each column represents the identified concepts in the literature. The identified concepts were coded (first cycle coding) using the inductive coding method, which develops progressively during analyzing the dataset without having the prior coding system and is usually influenced by the research questions [59]. Whenever a new concept was found, another column was added to the matrix. In this case, the discussed concepts in prior studies were recorded in a concept matrix, which then enabled all studies to be comparatively analyzed [60]. This technique is generally appropriate for identifying the themes and underlying concepts in previous relevant research [61].

The third phase consisted of organizing and grouping the concepts and their relationships by pattern coding (second cycle coding) according to their characteristics, assumptions, and highlighted themes based on the authors' scientific and conceptual reasoning [58,59]. Conceptualization is an iterative process, and a well-designed concept matrix can facilitate the process of coding the concepts and classifying them. To this end, another dimension was added to the concept matrix to handle the unit of analysis by grouping the concepts under major aspects and to enable schematic higher-order themes for building the synthesis framework [57,61]. This helps summarize the material from the first cycle coding into meaningful and manageable units of analysis and create a cognitive map, an evolving, integrated scheme for understanding interactions [59].

As [62] articulated, 'a conceptual framework explains, either graphically or in narrative form, the main things to be studied—the key factors, concepts, or variables—and the presumed relationships among them' (p. 18). The fourth phase, therefore, was to conceptualize the role of VGI in transformative resilience by synthesizing the identified concepts and their relationships and proposing a synthesis framework. Figure 2 shows the research process overview.

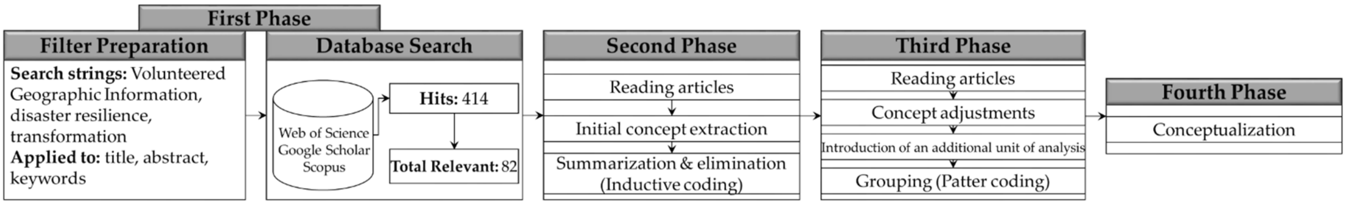

Figure 2. Research process overview.

4. VGI for Urban Transformative Resilience

Transformative approaches to urban resilience advocate creating and embedding innovations and novelties in governance, planning performance, and techno-social and technical exercises [18]. The logic is to endorse forward-looking decision making and predispose decision makers to adopt new ways of doing, thinking, and organizing [9]. Therefore, as promoted in international development agendas, measures need to be developed based on the open exchange and collaboration at multiple levels that leverage rapid communication, sustainable geospatial information systems, and geospatial technology innovations with near real-time access to geospatial information to improve the overall resilience of communities to disasters [1,2,4,19].

Profound transformations related to extensions of geospatial technologies based on new data sources through Digital Twins (a real-time digital representation of the physical world), Web 2.0, advances in G5 and mobile communications, blockchain, Big Data, volunteer crowdsourcing, digital volunteering, IoT, georeferencing, and geotagging have forced urban resilience processes to rethink several core concepts and methods they have relied on and to effectively use technological capabilities to proactively reshape crisis management, planning, and practices [12,17,18,21,63,64].

Data-enabled transformation pathways (data usage, data circulation, and data generation) of information, open and efficient exchange of geospatial information with advanced tools, and better urban analytics and simulations can greatly improve decision-making capabilities based on near-real-time information, reduce disaster impact, and enhance community resilience in the short, medium, and long term [17,48,65,66]. In this context, VGI offers alternatives and complementary opportunities to collect, share, and use geospatial data across different geographic and administrative scales that are otherwise extremely difficult and costly to collect [67] and provides near real-time, affordable, up-to-date, flexible, and fit-for-purpose geospatial information and supports the limited geospatial data infrastructures [22,68].

Transformative urban resilience promotes mechanisms with better and open access to spatial and risk-related information that enables better communication, knowledge sharing, and collaboration in decision-making processes across scales, actors, and citizens to foster synergies and minimize conflict [9,50]. The VGI process involves the use of modern information technologies and tools to create, organize, and disseminate geographic data, particularly in map-making, and are voluntarily developed and made available on the Web by individuals and non-formal institutions [69–72]. Figure 3 provides a schematic representation of the drivers and outcomes of transformative resilience regarding the capacities associated with VGI.

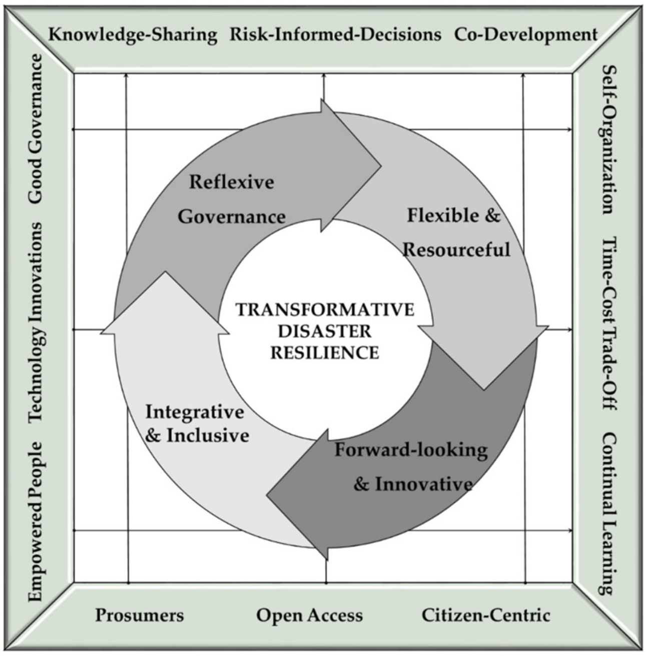

Figure 3. Drivers and outcomes of transformative resilience regarding VGI capacities.

The most successful example of VGI to date is OpenStreetMap (OSM), a citizen-driven initiative to create an open digital map of the world by digital and on-site volunteers that rivals many authoritative datasets in its richness and timeliness [73,74]. OSM has more than 6.2 million registered users and more than 6.4 billion features stored on the OSM platform [23]. Another example is Humanitarian OpenStreetMap (HOT), a volunteer-based group that applies the principles of open source and open data sharing to humanitarian aid and community development based on VGI and OSM, activates OSM mappers for crisis response or crisis mapping, and facilitates volunteer efforts by providing a tasking function; the HOT Tasking Manager [29]. Nevertheless, there is an emerged potential entry point for transformation, and that is through the integration of a collective community conscience via citizen-generated crowdsourced data to authoritative data [14,75]. Smarter management (collecting, sharing, updating, and using) of information, open and efficient exchanging of geospatial information with advanced tools, and better urban analytics and simulation to improve the ability to make real-time decisions, reducing the impact of disasters and enhance community resilience in the short, medium, and long term [48,66,76,77]. Since VGI is a multifaceted phenomenon, the next section explains the various factors or concepts that are critical to a deeper understanding of the extent to which VGI contributes to transformative resilience.

5. Toward Transformative Resilience—Main Aspects of Utilizing VGI

Based on the Concept Matrix developed (Section 4), 18 core VGI concepts related to urban resilience were identified (Figure 4). These concepts were presented in at least one of the resources, albeit in varying degrees of comprehensiveness and emphasis. To enable conceptual scaffolding, five main categories—social, economic, technical, institutional, and legal—were exploited to reflect the dimensions of utilizing VGI toward transformative urban resilience. The following subsections discuss each of these aspects and their contribution to transformative urban resilience.

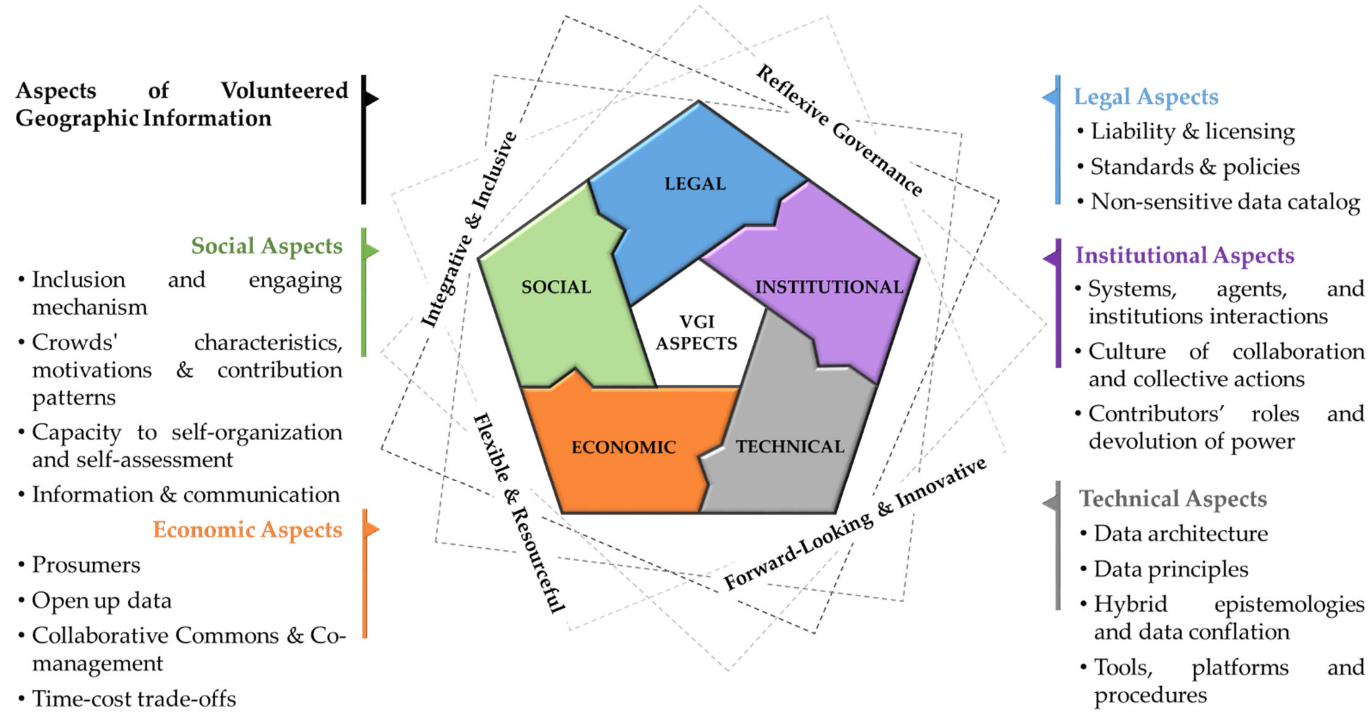

Figure 4. Core identified aspects of VGI.

5.1. Social Aspects

VGI introduces new social practices, projects, and processes whose success is driven by citizen contributions. Unlike conventionally produced forms of geographic information, volunteer efforts have added several different axes to structuring and representing geographic knowledge, producing and validating knowledge, and changing power relations [21,69]. Therefore, in this subsection, we intend to foreground the social aspects of VGI.

5.1.1. Inclusion and Engagement Mechanism

The bottom-up potential of VGI processes and practices raises questions about who is included or excluded in VGI practices (creating, using, or sharing information), why, and the extent to which they can reflect their knowledge [69]. Therefore, a participatory mechanism that is compatible with local characteristics, norms, and cultures can promote public participation and citizen engagement and help express local experiential knowledge [22]. Mapathons (community mapping events) are an example of how an engaging mechanism with a flexible structure through public calls can engage participants (e.g., citizens, youth mappers, or students) in mapping exercises and bring together a group of interested and motivated volunteers to collaboratively create, curate, and disseminate free and up-to-date spatial information, e.g., in disaster response activities [28,33,78]. This engagement mechanism not only provides volunteers with the opportunity to contribute to society based on collective action but also to learn new technologies through the use of web-based mapping [79,80].

5.1.2. Crowds Characteristics, Motivations, and Contribution Patterns

VGI is part of a profound shift in the way geospatial data are produced and disseminated by changing the roles associated with the creation and use of digital geospatial data [81]. VGI can be operated by a range of participants with different levels of expertise, experience and activeness, numbers, and responsibilities [72,82]. Motivations for contributing also vary from constructive and altruistic motivations (social reward, personal reputation, professional interest, making money, sense of community, instrumentality, and skill development) [21,69] to harmful contributions (massive or partial deletions and misinformation) [72,83]. Understanding crowd characteristics and formulating motivational strategies would therefore influence the outcomes of the VGI-based initiative [84–86]. Because the crowd is a relative term, contribution patterns, types, and roles of the crowd involved in the task may vary concerning the goals and roadmap of the initiative and need to be determined at an early stage [87–89].

5.1.3. Capacity to Self-Organization and Self-Assessment

The proactive role of citizens, community-led organizations, and e-participation intervention through digital technologies can illuminate the rise of self-organizing capacity in VGI-based communities [51,69]. Self-organization is a capability in which reorganization is endogenous, not forced by external factors, and enables novel self-assessment and reflexivity to facilitate innovative problem solving based on collective intelligence [90–92]. VGI, through collective technologies, actions, and tasks, empowers volunteers to self-organize and share information and resources to respond to disasters in a timely, responsive, and effective manner [22,93,94]. Through self-organizing community platforms (e.g., OSM, HOT, Missing Maps, etc., local communities, remote and distant volunteer networks can facilitate mutual self-organizing activities by collecting, validating, analyzing, and disseminating information before, during, and after a disaster, catalyzing a people-centered humanitarian approach that was long overdue [29,33,90].

5.1.4. Information and Communication

According to [95], disaster resilience initiatives typically have two types of communication paradigms for disseminating information: one-to-many and many-to-many. The former uses a top-down approach from one sender to a multitude of receivers (radio, television, and the Internet), while the latter uses a decentralized architecture to disseminate information among a multitude of transmitters and receivers by using services such as social media platforms, collaborative disaster mapping based on crowdsourcing, and social sensing. Therefore, innovative technologies based on new data sources, including VGI, are needed for integrated and flexible communication and an information system that enables multidirectional dialog among agencies, communities, and affected people [27,96]. VGI can make disaster-related information available to all in the cloud in near real-time for early warning of adverse events, within hours during and after a disaster, and for the early organization of spontaneous digital and non-digital volunteers after a disaster [27,55].

5.2. Economic Aspects

VGI and its mode of production provide open, timely, and freely accessible geospatial data that can be used in proactive disaster resilience initiatives to reduce disaster-related costs through better analysis, preparedness, effective risk communication, and economic value creation for the community [97]. This subsection examines the related economic aspect of VGI.

5.2.1. Prosumers

'Prosumers' (a portmanteau of provider and consumer) are consumers who have become their own producers through commons-based peer production in which large numbers of people work cooperatively over the Internet [98]. VGI and its associated processes, therefore, enable citizens or remote volunteers to actively contribute as prosumers to the production of geospatial content based on their individual or community needs and to use the produced data for their advantage [99]. This can be seen as an important innovation that combines sociotechnical practices and power relations supported by the so-called 'sharing economy' as a socioeconomic system based on sharing goods, skills, and services [30]. This brings prosumers together to collaboratively produce and use geospatial data in general and disaster-related geospatial data in particular. This enables better access to and use of information in near real-time and minimizes waste of resources due to duplication of effort [87].

5.2.2. Open Up Data

Creating an open data ecosystem for cities and resilience initiatives can facilitate innovation and data-driven disaster risk management [49]. The open-source data movement in principle enables any prosumer to educate, learn, and engage in information communities by exchanging know-how and expertise via Web 2.0 tools and platforms with varying levels of education, knowledge, and skills [30,100]. Unlike authoritative data, VGI can be collected, shared, used, and reused under an open-access license without technical limitations. This enables innovative and unrestricted reuse of data across sectors, leading to prosperity and better analysis at lower data-related costs [28,101,102]. The use of VGI-based platforms (e.g., OSM, OSMWiki, etc.), software and applications (e.g., InaSAFE, GeoNode, Open Data for Resilience Index, etc.), and open dashboards (e.g., Building Information Platform Against Disaster for Decision Making in Federal Nepal) that bring together a variety of data for disaster risk management can increase the prosperity of the scholars and citizens cooperating with the local government dealing with disaster risk management in a timely and efficient manner [76,103,104].

5.2.3. Collaborative Commons and Co-Management

A new economic paradigm—Collaborative Commons—is transforming the way humanity lives based on IoT, which facilitates collaboration to drive the social economy, optimize lateral peer production, promote universal access to information, and innovative and inclusive approaches by fostering the culture of sharing [98]. VGI as peer production of geospatial data can therefore increase productivity and connectivity through better access to timely data through the way it is produced and shared, based on user needs, backgrounds, and goals through collaborative engagement [105,106]. Co-management and co-production of knowledge (sharing power and responsibility between government and local resource users) [107] in VGI-based practices for disaster resilience can also bridge the data-related divide between different sectors and individuals from the local to the international level to generate and mobilize jointly produced geospatial data and knowledge and enable learning through uncertainty using a collaborative platform [30,97,108,109].

5.2.4. Time–cost Trade-Offs

Harnessing the power of today's communication technologies, prosumers share their location-based knowledge, goods, and services at lower marginal costs [98]. In the context of disaster resilience, VGI enables the faster sharing of diverse disaster-related geographic information at a fraction of the cost associated with traditional data collection and dissemination [63]. Internet facilitation enables agencies and citizens to collaborate, collect, and disseminate large amounts of geospatial data in near real-time through digital and on-site volunteers by reducing the limitations associated with traditional approaches, such as high costs and slow access to near real-time data [68,109]. In addition, new data and technologies (crowdsourcing, digital volunteering, mobile communications, etc.) that enable real-time dynamic monitoring, multidirectional communication, and situational awareness can advance urban disaster resilience initiatives and overcome traditional, outdated, and costly methods. [27].

5.3. Technical Aspects

Decision makers and citizens increasingly require high-resolution data, both temporal and spatial, for successful disaster resilience initiatives. The large-scale and timely observations are, therefore, unique advantages that can be provided by VGI [63,74]. This subsection examines the technical aspects of VGI to highlight the opportunities and challenges associated with utilizing such data.

5.3.1. Data Principles

Access to open, free, and high-quality datasets (e.g., accurate, relevant, complete, reliable, and timely data) is necessary for efficient, inclusive, and innovative resilience planning [20,102,110,111]. In the field of VGI, the issue of quality is challenging because the method of data collection deviates from the strict official data collection frameworks [112]. Several research studies assess the quality of VGI based on the aforementioned elements (see, [33,110,112–116]. However, VGI provides inherent quality assurance due to the 'power of crowd' principle known as Linus's Law and can provide accurate and trustworthy information [117]. Ensuring data accuracy (e.g., positional, thematic, semantic accuracy, and topological consistency) in VGI-based resilience initiatives is critical and should reflect a real-world situation considering time-critical situations [84,118].

Data relevance comes into play when irrelevant data collection should be avoided and a fit-for-purpose approach to data collection and integration should be considered [68]. Data completeness is an essential component of data quality and is closely related to validity and accuracy. For example, in map-based VGI, statistics on the number of objects, attributes, and values can be tracked to measure the degree of completeness or the percentage of missing data in a region [84,119]. Reliability also means that the user has access to the maximum amount of information with the best possible timeliness [120]. Data timeliness shows how accessible and up-to-date the information is, leading to better analysis and decision making without wasting time in time-critical situations. The experience of OSM Haiti showed that volunteers who collaborated around OSM could quickly create accurate and trusted information when institutional data were lacking in time-sensitive situations [65,121]. Moreover, VGI has the potential to be a timely source for disaster preparedness and early warning [31,84,122]. An example is the Open Cities project by OpenDRI in Sri Lanka, in which crowdsourced VGI data and tools were adopted to collect useful data for risk preparedness and exposure mapping [100].

5.3.2. Data Architecture

Data architecture is the process that governs and standardizes how organizations collect, assess, create, validate, consolidate, distribute, and use data by conceptualizing, contextualizing, and modeling data [70]. Therefore, a systematic approach to creating, curating, analyzing, and using VGI to improve urban resilience must be employed by relative institutions or foundations guiding contributors to completing the tasks [123]. Since VGI often lacks standard metadata due to a lack of quality control in data-collection processes [87], establishing a practical and consistent guideline for data architecture based on project goals can be instrumental in developing a common operating picture for all stakeholders and contributors [113].

5.3.3. Hybrid Epistemologies and Data Conflation

The authors of [124] discussed that VGI is itself a socially constructed epistemology based on the embedding of a labor relationship (volunteers as free laborers), a reference relationship (experts versus amateurs), and a governance relationship (volunteers as citizens) and must be treated independently. In addition to traditional authoritative data, which are typically associated with high costs, outdated data, and restrictive licensing terms for urban resilience initiatives, VGI can be considered a complementary and important source that can be integrated with authoritative datasets [112,125]. Although there are fundamental epistemological differences between VGI and authoritative data (existing levels of expert oversight, standards, and the inherent heterogeneity of VGI), organizations can leverage VGI based on their goals within a formalized process for data collection and multi-level collaboration when they have clear requirements, such as a faster update cycle, capturing additional or real-time attribute information, engaging the community, or reducing the cost of geospatial data acquiring [20,81]. A shift toward hybrid epistemologies and data conflation processes based on situating and adopting VGI by governments may provide an opportunity for data-driven decision making [23,87,126].

5.3.4. Tools, Platforms, and Procedures

Location-based and GPS-based services (e.g., maps, social media applications, tracking, and information services) for disaster information and resilience, as well as open-source tools for realistic natural hazard impact scenario building for better planning, preparedness, and response, can collect information from users and then provide them with actionable information, often through a map interface [74]. Several methods support the collection and dissemination of geospatial data by volunteers, e.g., OSM, WikiMapia, Geo-Wiki, documentation websites (e.g., Siteleaf), HOT's Tasking Manager (campaigning, data creation, and validation), scanning by drone and 3D laser, and smartphones (e.g., MapSwipe app) (e.g., MapSwipe App) [18,63,68,111,127]. Crisis or resilience dashboards and urban digital twin platforms can also serve as platforms to aggregate multiple data from different data sources (e.g., social sensing, weather, road traffic, pollution, etc.) to provide real-time information to citizens and improve transparency, efficiency, and resilience [103,128]. Required practices, such as managing a Mapathon (open digital community mapping) using the Missing Maps planning checklist, and developing workflows, roadmaps, frameworks, and catalogs for fit-for-purpose data collection, will ensure the contextualizing process of resilience improvement based on goals, local values, facts, and needs [29,101,129].

5.4. Institutional Aspects

The institutional structure has a direct impact on the availability and accessibility of geospatial data and can significantly hinder or facilitate the process of geospatial data collection, usage, and sharing [130]. Institutional arrangements as a link between agents and systems can determine the extent of collaboration in decision making and collective learning [131]. Since the VGI paradigm may create a new relationship between governments and citizens and motivate citizens to actively contribute to disaster resilience initiatives [22], the corresponding components of the institutional aspects of VGI are discussed in the following subsections.

5.4.1. Systems, Agents and Institutions Interactions

Urban resilience functionality is characterized by dynamic interactions among urban systems (e.g., built environment, critical infrastructure, and essential services), agents (people and organizations), and institutions (e.g., policies, laws, social norms, etc.) that connect systems and actors and mediate their interactions [35,132]. The use of VGI can be adopted based on the definition of an institution with specific rules and regulations compatible with desired structures or formalities [32]. However, the VGI structure can influence institutional mechanisms that have evolved across spatial, temporal, and sectoral boundaries, strengthening collaboration among different stakeholders and creating a new relationship between systems and actors through the provision and application of new geospatial knowledge [22,69,88,125].

5.4.2. Culture of Collaboration and Collective Actions

Collaborative disaster resilience planning requires collective efforts from multiple government agencies, nongovernmental organizations, the private sector, communities, and civil society [22,125]. Therefore, sufficient information flow with transparency, accountability, and responsiveness plays an important role. VGI and related technologies can be used to engage relevant institutions and citizens to disseminate and use collective geographic data toward collaborative resilience building. Collective action requires time and resources. Institutions and agencies must be prepared to strategically engage and manage dynamic information flow and ideas from citizens and other institutions [74,133].

5.4.3. Contributors' Roles and Devolution of Power

Urban resilience governance and planning in many countries is top-down and sector-based. However, governance systems (i.e., the process of decision making) are likely to be collaborative, participatory, and inclusive to enhance community resilience [134].

The emergence of VGI potentially challenges traditional institutional forms of disaster management. Crowdsourcing processes are defined by [135] defined as ‘the process by which the power of the many can be leveraged to accomplish feats that were once the province of a specialized few’ (p. 56). VGI not only enabled the active contributions of individuals but also offered new norms and forms in information conditions as well as power relations at all levels that can lead to integrating authoritative epistemologies with a more open and local representation through an appropriate collaboration mode [69,125,136]. However, there is an ongoing debate about the level of authorities’ involvement and enforcement of regulations, the scope, structure, and outcomes of VGI projects that are mainly citizen-led initiatives [67,81].

5.5. Legal Aspects

The legal aspects of VGI are complex, as legislation typically lags behind technological advances and often varies across countries and between citizens, national mapping agencies, and commercial companies [74]. Legal concerns are likely when using VGI in official systems. The compilation methods of VGI are very different from those of structured datasets, and although there may be restrictions on their integration in official databases, VGI can contribute to the enhancement of place-based knowledge without incurring legal consequences [68]. In this sense, platform operators, users, and contributors of VGI must all be attentive to the legal issues that may be triggered by their activities [137]. In this subsection, we highlight some of the key issues related to VGI in the context of urban resilience.

5.5.1. Liability and Licensing

The main problem related to liability is who is responsible and under what conditions when socioeconomic losses occur or wrong decisions are made. However, under the VGI model, VGI contributors cannot be held legally responsible for their contributions [24]. Therefore, disclaimers or data quality notices are necessary to limit potential liability [137]. In addition, VGI initiatives should establish procedures and develop protocols to deal with insufficient quality when providing information about legal disclaimers or licensing agreements [68].

Part of the motivation for developing VGI was to provide data that were voluntarily generated and could be used relatively free of licensing restrictions due to the lack of access to costly authoritative datasets [24]. Since different forms of licensing and terms of use may limit the ability to use such information in the case of the need to merge datasets with different licensing strategies, possible integration scenarios can be defined by stakeholders [74]. Moreover, VGI does not have legal status in many countries. Therefore, the legal implications for volunteers and project developers should be clarified, as the data-collection process for VGI is different from formal datasets [68].

5.5.2. Standards and Policies

Open source and user-generated geospatial content and its foundations (such as the Open Source Geospatial Foundation) are expected to grow at both the national and international levels (the Open Geospatial Consortium and the International Organization for Standardization) [70,138]. In this sense, the creation and development of new legal frameworks, guidelines, and open standards for different VGI platforms or tools seems necessary. This will not only lead to the facilitation of interoperability and data exchange but also to the protection of the integrity and objectivity of these data to prevent the emergence of data-related risks and mitigate existing ones [138]. Standard models for linking administrative datasets to other datasets or for data exchange on the Web to integrate VGI into spatial data infrastructures based on paradigms such as the Linked Data paradigm [139] also need to be developed [23,25].

Furthermore, the necessary policies should be defined at different governance levels, such as an Open Data policy and an integrated data and service sharing policy, to increase the chance of a functioning system for resilience initiatives that build on technology, community engagement, and a smart governance structure while reducing the potential impact of using VGI in decision making [20,25,74].

5.5.3. Non-Sensitive Data Catalog

According to the Sendai Framework, it is important to make non-sensitive disaster-related information publicly usable and freely available based on open exchange for successful disaster risk communication, mitigation, and prevention following national laws. The sensitivity of the information, whether it is commercially, socially, culturally, or technically sensitive, is a legal issue for governments [77]. Therefore, data collection in VGI-based initiatives requires operational strategies or protocols for the intended purpose, formulation of the plan, and implementation of a project according to a country's national policy [32,68]. The critical step is to define a fit-for-purpose approach to geospatial data collection that is flexible, inclusive, participatory, affordable, reliable, achievable, and extensible [140,141]. The design of the data catalog also requires close collaboration among working groups to define its architecture based on a low-risk, high-benefit approach in an iterative process that requires upfront legal, ethical, and technical research at the local level to capture non-sensitive information and preserve the privacy and security of disaster-prone communities [22,65].

5.6. Main Lessons Learned from VGI Practices

Some of the key lessons learned from VGI-based disaster risk management initiatives include the following: Coordination among participating organizations and volunteers is essential to take full advantage of human resources and technical innovations and to avoid duplication of data and waste of resources; government and community cultural conditions must be known to choose an appropriate approach; the process is best kept at the community and local levels to ensure sustainable curation; it is crucial to have a transparent and flexible stakeholder mapping and data model that can be easily adapted to community needs, available tools, and resources; consensus building among those who need and control data and appropriate development of open data policies can address legal and regulatory issues; concerns about the quality of datasets generated can be addressed through quality control and a progressive process of data improvement [18,30,49].

6. A Framework to Leverage VGI toward Transformative Urban Resilience

This section proposes a synthesis framework (Figure 5) developed based on the key aspects outlined in Section 5. The framework was designed using a combination of current literature and resources obtained from previous studies. A conceptual framework is a tool that contains a set of logical building blocks and their interconnections [62]. Thus, the proposed conceptual framework is not just a collection of aspects but rather a construct in which each aspect has an integral effect on utilizing VGI, as described below. Likely, clarifying the various aspects in the form of a conceptual framework could support the potential process of employing VGI in transformative disaster-resilience initiatives within three main phases (columns), namely resourceful planning and creative data collection, cooperative design and forward-looking analysis, and generation of added value and collective learning. Legal, institutional, technical, and socioeconomic aspects of VGI are shown in different colors (rows).

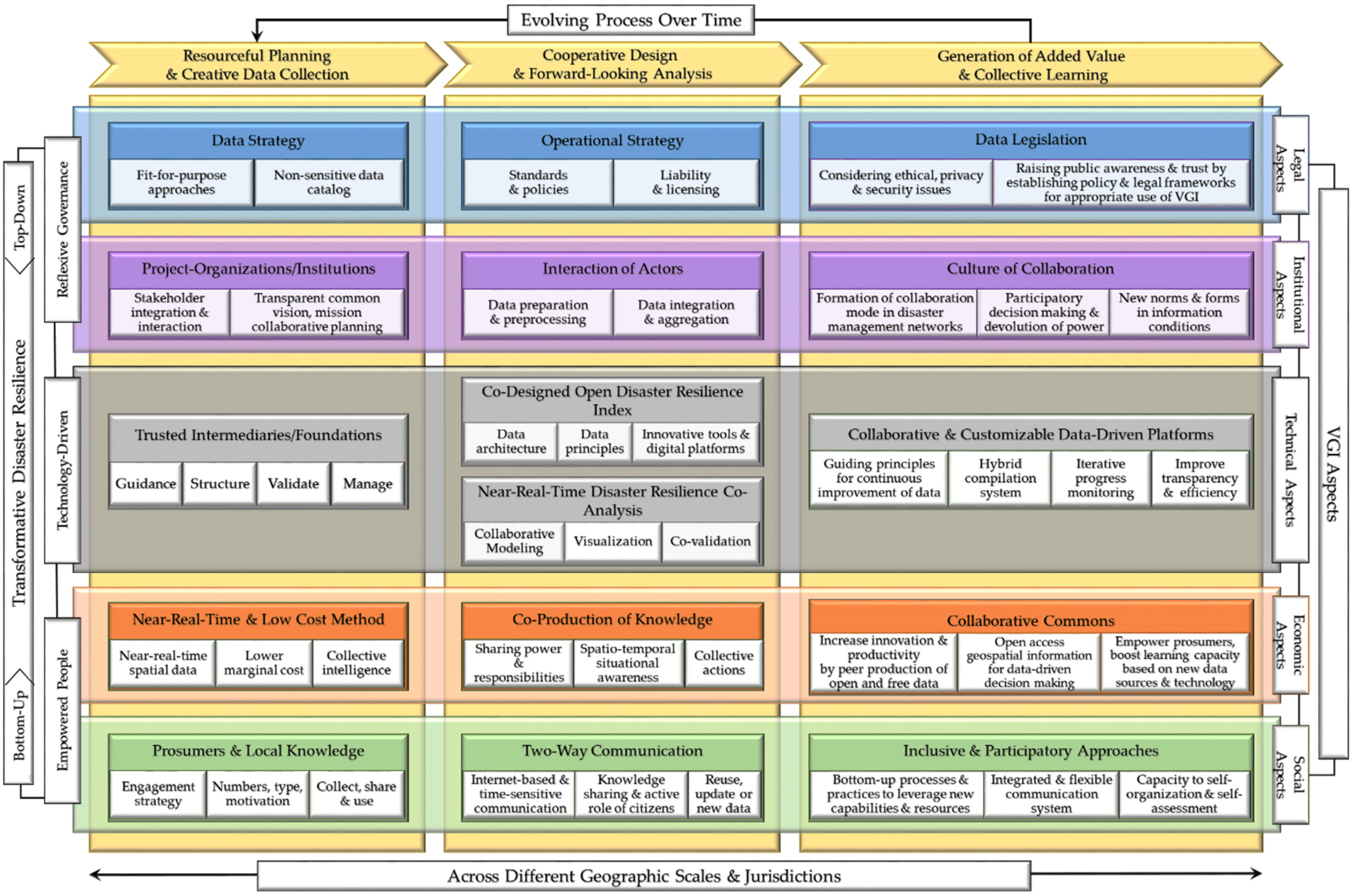

Figure 5. A framework for leveraging VGI toward urban transformative resilience.

From a bottom-up perspective, legal and institutional issues can enable or hinder a VGI-based project. Therefore, as part of a reflexive governance approach, project organizations or institutions in the planning and data collection phases should consider developing operational protocols based on a fit-for-purpose approach to collecting non-sensitive data while considering the data policies and regulations of the relevant jurisdiction. This requires an interactive, inclusive, and multiscale process of establishing shared visions, missions, and practices about what they want to achieve and how. The co-design and co-analysis phase should consider legal obligations for managing VGI, linking or integrating that into administrative datasets for liability and licensing arrangements, and revising them as needed by adopting open-source data policies, standards, and licensing strategies considering privacy, security, and ethical issues. Developing new data legislation and increasing public awareness and trust for the appropriate use of VGI can be achieved through collective and cumulative learning processes.

Since building community resilience depends on empowering people and considering bottom-up approaches, it is important to develop a mechanism that encourages citizen participation. Prosumers' and citizens' contribution is the most important part of any VGI initiative because of its bottom-up structure and socioeconomic aspects. The engagement mechanism in any VGI initiative depends on the goals of the project and should focus on encouraging the type of crowd that is more likely to make effective contributions (collecting, sharing, updating, and reporting the required geospatial data). However, in general, this enables leveraging new capacities and resources and developing their self-organization capacities through collaborative learning and work within a flexible communication system over open Web-based platforms across all sectors. By facilitating the Internet, agencies and citizens can collaborate and disseminate large amounts of geospatial data in near real-time and at a lower cost. This enables rapid access to location-based data, time-sensitive two-way communication, co-production of location-based knowledge, situational awareness, collective action, and collaborative coordination in the context of transformative resilience. Thus, value is added by enabling prosumers and citizens to increase their learning capacities based on new data and technologies and digitalization for productivity and growth.

Reflexive governance cannot be achieved without empowered people, and technology-enabled approaches can act as facilitators in this regard. Technology and data innovations contribute to transformative resilience in the face of uncertainties associated with disasters. Trusted intermediaries or foundations (e.g., OSM, HOT, etc.) provide guidance (e.g., learning guides and community events such as Mapathons) and structure (mapping, tagging, labeling, etc.) to volunteers, and validate and manage collected data through systematic approaches on existing or newly developed platforms and have better overall quality control. Efficient, inclusive, and innovative resilience planning requires access to high-quality and timely data sets (e.g., accurate, relevant, complete, reliable, and timely data). Therefore, defining a practical and unified data architecture and catalog based on the project goals for co-designing an open resilience index is necessary to develop a common operating picture for creating, curating, analyzing, using, and sharing information among stakeholders and systems. Innovative tools and methodologies (e.g., IoT, ML, Digital Twin, etc.) can be applied to VGI to enable collaborative modeling, real-time analysis, co-validation, and better visualizations. This facilitates innovative problem solving based on collective intelligence and may overcome the potential spatial and temporal limitations of traditional approaches. The added value of such an approach could be a collaborative and adaptive hybrid data-driven ecosystem that enables continuous improvement of geospatial data (leveraging the power of traditional knowledge systems and citizen science), iterative progress monitoring of disaster resilience dynamics, and improved transparency and efficiency among institutions, agencies, and the public, as well as informed decision making.

The framework proposed in this study should therefore be considered as a guide for researchers and practitioners on how VGI can be implemented in disaster resilience initiatives, taking into account a comprehensive understanding of the complexities and interconnections of legal, institutional, technical, economic, and social aspects within each jurisdiction. Indeed, a shared understanding of the benefits of emerging trends in geospatial data, smart technologies, and spatial analytics using new data and tools can bring government, industry, and communities together to effectively build sustainable and resilient communities.

7. Key Challenges and Limitations

VGI-based initiatives may offer many opportunities to contribute to transformative pathways to disaster resilience, but they also present a number of challenges. In this study, the concerns and challenges associated with using VGI for transformative resilience are structured around the five thematic aspects discussed in Section 5.

With legislation typically lagging behind technological developments, VGI presents numerous challenges to existing legal and policy structures related to spatial data, information, and maps. There are limitations on its adoption in official databases in various jurisdictions. Therefore, the formation and development of new legal frameworks, policies, and open standards for open-source and user-generated spatial data content and foundations must be considered at all governance levels and researched further to ensure the integrity and objectivity of this data and prevent the emergence of risks or mitigate existing risks.

The institutional structure has a direct impact on the availability and accessibility of geospatial data and can significantly hinder or facilitate the process of collecting, using, and sharing geospatial data. In most jurisdictions, governments play a central role in urban resilience practices, and professionals within organizations have primary responsibility for geospatial data collection and maintenance. However, a VGI paradigm would suggest a new relationship between governments and citizens that may be challenging for national institutional structures that are not linked to local and community processes. Therefore, the level of interest and active participation of government agencies, as well as regulatory enforcement, may affect the progress and outcome of VGI-based initiatives and may slow down the creativity and innovation of VGI projects.

From a technical perspective, the emergence of VGI as Big Data has exponentially increased the volume, velocity, and variety of geospatial data generated, and the coupling with geosocial applications has led to a fundamental shift in how these data are maintained, stored, processed, and used [142,143]. This includes the search for appropriate synthesis methods, the integration and use of these data along with government-managed geospatial data for urban disaster resilience, and the need for new tools for data management, curation, and analysis [143,144]. In addition, VGI may also present obstacles in terms of reliability, validity, and intrinsic and extrinsic quality of data and metadata [143]. Therefore, based on the project goals, it is necessary to develop a data protocol between the involved actors and systems to overcome these limitations.

On the socioeconomic side, issues such as local differences, the extent of community acceptance of technology, the digital divide, marginalization of certain groups, openness to digitization, reliance on digital data collection devices, privacy concerns, and ethical issues in collecting and publishing VGI in practice need to be considered and should be further explored in future studies. Other important concerns include capacity building and resource allocation, increased trust in data and transparency, and collaborative decision making and coordination at the local level that need to be addressed in VGI-based practices.

Although the comprehensive framework proposed in this study attempts to provide an overall picture of VGI capacity for transformative resilience while addressing the complex issues that are considered missing knowledge in the field of urban resilience, the rapid advances in technology, society, and digital innovation as influential drivers may influence the direction of future research and provide opportunities to refine and expand the framework. In addition, we recognize that the application of the framework will also be an opportunity for further study and is a limitation of this study, as it is beyond the scope of a single study.

8. Conclusions

Transformative resilience aims to achieve reflexive governance with empowered people, using technology-enabled approaches as facilitators. This article, therefore, considers the key characteristics of transformative resilience to explore the various aspects of VGI for strengthening community resilience in the face of disasters and to fill the knowledge gap in the two areas. Qualitative analysis of available resources led to the identification of 18 key VGI concepts in the categories of legal, institutional, social, economic, and technical, providing a multifaceted view of VGI adaptation for transformative resilience. To develop a deeper understanding of how VGI can be considered in research and practice, the framework was proposed to provide a comprehensive foundation as a guide for VGI-based initiatives with a broader consideration of socioeconomic, techno-social, legal, and institutional issues. Indeed, building upon our framework with its flexibility, future research can explore new aspects of VGI in light of new insights and learning through resilience processes while addressing the relevant challenges.

VGI-based models can be considered either as stand-alone or complementary mechanisms when and where conventional approaches are less suited to foster collective community resilience or culture of collaboration, and administrative datasets are less appropriate for providing open, accessible, and timely geospatial information to both the community and decision makers. Given the increasing access to VGI and related technologies, it is timely to assess their opportunities, challenges, and effectiveness through comprehensive empirical studies at multiple scales and contexts in future research and practical projects to effectively incorporate VGI into resilience transformation processes.

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CHAPTER 5

NEAR REAL-TIME ANALYSIS OF CROWDSOURCED SOCIAL MEDIA DATA AND AN ONLINE SURVEY FOR DISASTER RESILIENCE ENHANCEMENT (IDIOGRAPHIC/BOTTOM-UP APPROACH)

This chapter aims to capture the dynamic processes of resilience and to complement our understanding of resilience capacities within large communities of individuals and spatio-temporal extent of a flood disaster situation within a timely situational analysis. Therefore, within an idiographic or bottom-up approach using crowdsourcing social media, Twitter messages (public attitudes) on various topics within disaster phases are coded in near real-time as the flood disaster hit Germany in July 2021 in parallel with the coronavirus pandemic. In addition to semantic (textual) analysis, spatiotemporal patterns of online disaster communication are also assessed. As an additional data layer, an online survey of responders (key stakeholders) involved in flood relief was conducted with open-ended questions to determine their perceptions of issues and capacities. To extract latent topics from the corpora of both data layers, Latent Dirichlet Allocation (LDA) was used as an unsupervised machine-learning approach. Based on the knowledge domain, the extracted topics discussed online were then compiled into five disaster resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) to reflect people's and stakeholders' perceptions and expectations of improved disaster resilience as well as to account for the change in inherent resilience of communities benchmarked by top-down approaches. The use of this real-time collective sensing approach can also provide valuable information ranging from early identification of needed actions to insights for developing resilience strategies to increase evidence-based resilience to unforeseen disasters.

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The wisdom of crowds for improved disaster resilience: a near-real-time analysis of crowdsourced social media data on the 2021 flood in Germany

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Abstract

Disaster resilience in times of climate change underscores the importance of reflexive governance, facilitation of socio-technical advancement, co-creation of knowledge, and innovative and bottom-up approaches. However, implementing these capacity-building processes by relying on census-based datasets and nomothetic (or top-down) approaches remains challenging for many jurisdictions. Web 2.0 knowledge sharing via online social networks, whereas, provides a unique opportunity and valuable data sources to complement existing approaches, understand dynamics within large communities of individuals, and incorporate collective intelligence into disaster resilience studies. Using Twitter data (passive crowdsourcing) and an online survey, this study draws on the wisdom of crowds and public judgment in near-real-time disaster phases when the flood disaster hit Germany in July 2021. Latent Dirichlet Allocation, an unsupervised machine learning technique for Topic Modeling, was applied to the corpora of two data sources to identify topics associated with different disaster phases. In addition to semantic (textual) analysis, spatiotemporal patterns of online disaster communication were analyzed to determine the contribution patterns associated with the affected areas. Finally, the extracted topics discussed online were compiled into five themes related to disaster resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative). The near-real-time collective sensing approach reflected optimized diversity and a spectrum of people's experiences and knowledge regarding flooding disasters and highlighted communities' sociocultural characteristics. This bottom-up approach could be an innovative alternative to the traditional participatory techniques of organizing meetings and workshops for situational analysis and timely unfolding of such events at a fraction of the cost to inform disaster resilience initiatives.

Keywords: disaster resilience, Twitter, online survey, Topic Modeling, Latent Dirichlet Allocation, 2021 flood Germany

1. Introduction

In July 2021, country-wide flooding in Germany affected about 40,000 people, claimed more than 197 lives and 1000 injuries, and caused total damage of about $40 billion ("EM-DAT," 2022). The high death toll (the highest since 1962) in the world's fourth largest economy, unfamiliar with this scale of death and destruction, raised questions about the resilience of Germany to such unforeseen floods and its readiness to deal with the impacts of climate change (Fekete & Sandholz, 2021). Moreover, the recently published 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) warns that such extreme events will continue to increase in frequency and severity in the coming decades ("IPCC," 2022). This underscores the need to shift from a reactive to a proactive approach in addressing climate-related hazards and unforeseen disasters and improving community resilience. To improve community resilience, it is critical to overcome the limitations of nomothetic (top-down) resilience approaches that use a set of indicators to characterize resilience and statically measure inherent baseline conditions (Cutter, 2016; Yabe et al., 2022). Complementing this, idiographic (bottom-up) approaches to disaster resilience that leverage collective local knowledge and information, reflect the resilience capacities of communities, and propose place-based resilience strategies are urgently needed.

Furthermore, Web 2.0 has changed how people communicate, seek, exchange, and generate knowledge on online social platforms (Ziegler, 2022). In particular, social media channels such as Facebook, Instagram, and Twitter, as passive crowdsourcing platforms, provide unique venues in an online space through which people's collective place-based knowledge, experiences, and perceptions can be captured (Lamoureux & Fast, 2019; Muñoz et al., 2020). These platforms also enable the public to produce geographic information on a voluntary basis, which can be referred to as Volunteered Geographic Information (VGI) (Degrossi et al., 2019; Elwood et al., 2012). On the one hand, this allows the wisdom of crowds to be captured in specific spatial and temporal units through researchers' large-scale observations and social sensing techniques, so-called passive crowdsourcing (Fan et al., 2020; Ghermandi & Sinclair, 2019). On the other hand, using these platforms enables different levels of participation and engagement of citizens who are not otherwise involved in scientific or administrative activities (Haklay, 2013; Howe, 2006). Twitter, in particular, offers a unique perspective because the social network is widely shared, user-driven, and network-based. These characteristics of Twitter as an open-source micro-blogging platform make it a valuable and useful source of data, as each tweet is typically linked to temporal-spatial and textual information, resulting in relatively homogeneous and comparable corpora for understanding the dynamics within large communities of individuals due to the relatively short message size (Rachunok et al., 2021; Rudra et al., 2019).

Twitter has proven useful for situational awareness, distributed problem-solving, and collective action, especially during crises (Ghermandi & Sinclair, 2019). However, there is a shortage of studies that harness the power of these valuable data sources that provide specific local and contextual knowledge based on collective and foundational insights about individuals and communities (collective intelligence) to inform community resilience from the bottom up (Fan et al., 2020; Rachunok et al., 2021). Therefore, this study presents one of the first attempts that harness social media (Twitter) data and an online survey to aggregate flood-related individual judgments and inform flood resilience in Germany through a bottom-up collective sensing approach.

To this end, after mining flood-related tweets (with a set of hashtags for each disaster phase) from July 12 to July 31, 2021 (short-term before, during, and after the flood disaster) and pre-processing the raw data, we performed textual, spatial, and temporal analysis for each phase. For the textual/semantic analysis, Latent Dirichlet Allocation (LDA) was used as an unsupervised machine learning model for Topic Modeling to obtain latent topics of the corpora (Blei et al., 2003). Kernel Density Estimation (KDE) at the state level and temporal clustering of tweets in different disaster phases were performed to analyze the spatiotemporal characteristics of disaster-related tweets. As an additional data layer, we conducted an online survey among the responders of the September 2021 flood disaster. We also modeled the topics (using LDA) that were highlighted in open-ended questions by this stakeholder group in German emergency management. Finally, the results of the Twitter Topic Modeling and the online survey were compiled into different themes of preventive, anticipative, absorptive, adaptive, and transformative resilience capacities for evidence-based improved resilience.

The practical implication of this novel and interactive web-based approach is grouping a large number of judgments to optimize the diversity and spectrum of experience and knowledge of contributors (wisdom of crowds) with different backgrounds on flood resilience in a timely manner. Passive crowdsourcing integrated with online surveying could also be an alternative to traditional participatory methods and techniques that organize meetings and workshops for situation analysis and unfolding such events. Finally, reflecting on the collective intelligence, perceptions, and expectations within the decision-making process contributes to identifying short-term priorities for action and developing place-based disaster resilience strategies based on the community's medium- to long-term needs and capacities.

2. Background

2.1. Disaster resilience

International agreements and agendas compete to address the challenges posed by natural hazards and the impacts of climate change. In the Sustainable Development Goals (SDGs), target 1.5 calls for "...strengthening the resilience of people in vulnerable situations and reducing their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters", Goal 11 calls for "making cities and human settlements inclusive, safe, resilient and sustainable" in line with the Sendai Framework (11.b), while Goal 13 calls for urgent climate action (United Nations, 2015b). The Sendai Framework for Disaster Risk Reduction also prioritizes building resilience to reduce disaster risk, understanding disaster risk, and enhancing disaster preparedness for effective response and building back better in recovery and rehabilitation (United Nations, 2015a).

In academic circles, there are numerous theoretical and operationalizable frameworks on disaster resilience, that emphasize the extension of *preventive* (ability of systems to adopt sustainable pathways and reduce vulnerability, presence, or impact of hazards), *anticipative* (ability to understand risks based on risk data and scenarios to predict where, when, and whom disaster will affect), *absorptive* (the ability of systems to withstand change and bounce back to a previous state), *adaptive* (adjustment to change and reorganizing without significant qualitative changes in functions or structures), and *transformative* (transformation through learning, self-organization, and exploration of new pathways along with flexibility and substantial modifications to existing structures) capacities within different resilience dimensions (individual, social, economic, institutional, infrastructural, environmental, and community capital) to build and enhance overall disaster resilience at multiple levels (Asadzadeh et al., 2015; Assarkhaniki et al., 2020; Béné et al., 2012; Cutter et al., 2008; Khazai et al., 2015, 2018; Manyena et al., 2019; Moghadas et al., 2019; Rajabifard, 2020).

However, the importance of building disaster resilience by considering the role of good governance, empowered people, and technology-driven approaches to create solutions in a place-based, inclusive, and forward-looking manner has compelled recent urban resilience initiatives to focus on the concept of transformative resilience, especially when incremental adaptation and conventional resilience planning are insufficient (Asadzadeh et al., 2022; Moghadas et al., 2022; Rajabifard et al., 2021). Transformational approaches emphasize the role of technological-social development and the integration of new data (VGI, social media, crowdsourcing, etc.) that can contribute to improved situational awareness and the development of indicators that reflect soft attributes of resilience (e.g., community solidarity, learning from the past, knowledge of climate resilience) (Fekete & Rhyner, 2020; Feldmeyer et al., 2020; Moghadas et al., 2022; Yabe et al., 2022).

Disaster Risk Management (DRM) activities also focus on strengthening the social and economic resilience of individuals and societies in the face of disaster risk through the process of *prevention* (activities and measures to avoid existing and new disaster risks), *preparedness* (effectively anticipate, respond to and recover from the impacts of disasters), *response* (actions taken directly before, during or immediately after a disaster), and *recovery* (rehabilitation and restoration of services and facilities essential to the functioning of a community in the short term and reconstruction, rebuilding, and sustainable restoration of affected systems and communities in the medium to long term), and utilizing a mix of different financial instruments, such as national emergency funds, contingency credit, insurance, and reinsurance (Fekete et al., 2020; Manyena et al., 2019; UNDRR, 2022). With this background, Figure 1 shows a schematic representation of disaster resilience capacities within the DRM cycle.

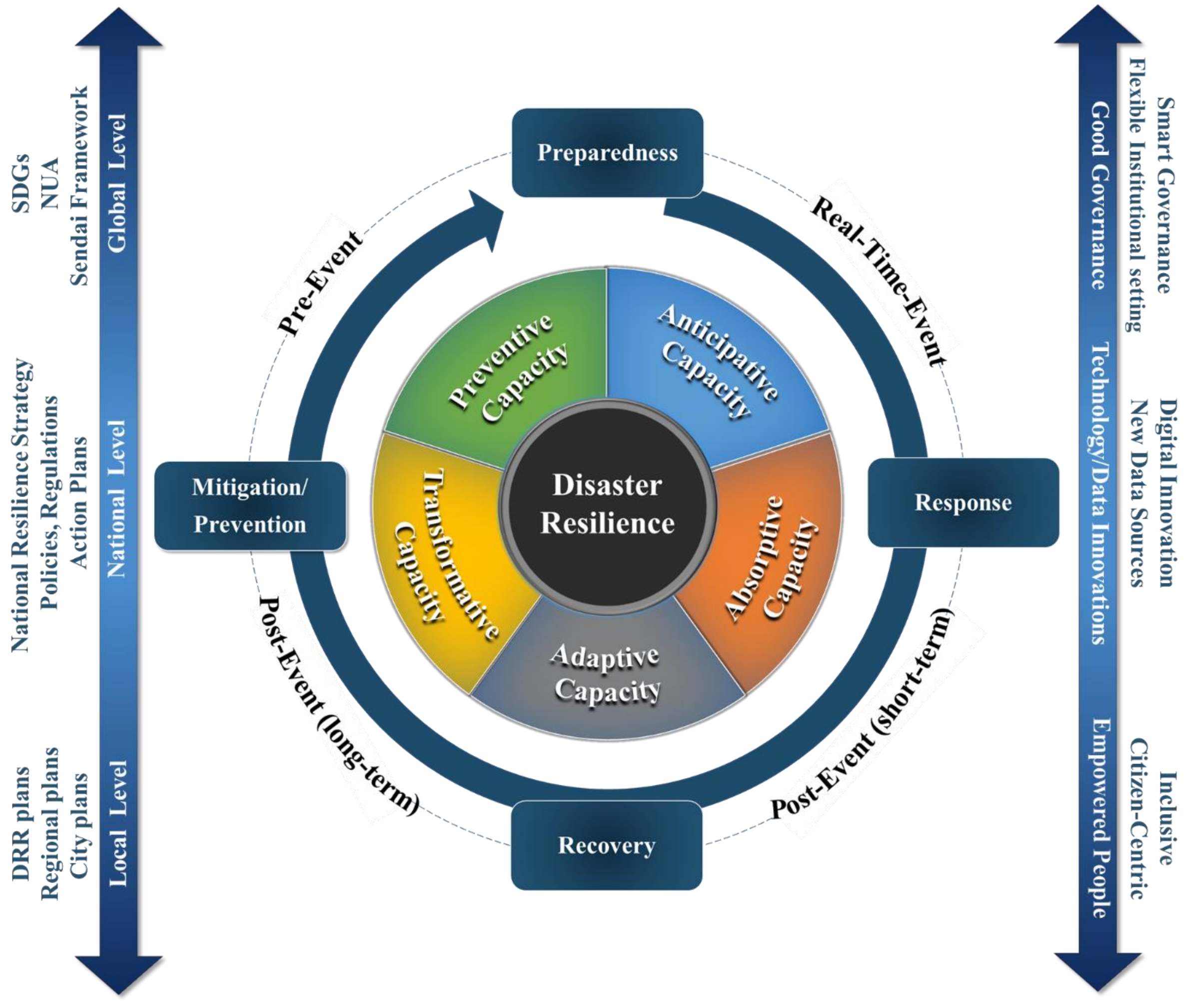


Figure 1: Schematic representation of disaster resilience capacities within the disaster management cycle

Although the representation of the DRM cycle has been criticized because it lacks the idea of progress, building back better, and learning, it is still frequently used. We also use it here only schematically to provide a link to DRM and disaster resilience capacities.

2.2. Crowdsourced social media in disaster resilience

The Sendai Framework promotes the use of information and communications technology innovations to improve data collection, analysis, and dissemination, as well as the increased use of social media and mobile networks to support real-time, data-driven measures for successful disaster risk communications (United Nations, 2015a). Social media platforms enable access to near real-time, affordable, up-to-date, and fit-for-purpose geospatial information that can be complementary data sources in disasters for better situational awareness (Fan et al., 2020; Moghadas et al., 2022). Social media platforms, moreover, enable passive and active (when they voluntarily share spatial information) participation by citizens who are not otherwise involved in disaster-related activities (Muñoz et al., 2020; Tzavella et al., 2022). In this context, crowdsourcing approaches like “People as Sensors” and Collective Sensing (Haklay, 2013; Resch et al., 2016) can play a crucial role in better disaster resilience planning.

Given the increasing use of social media crowdsourcing and new VGI data sources such as Twitter, Wang et al. (2021) articulate that Twitter could be used to monitor people's responses at different phases of disasters to better understand resilience. They examined the relationship between Twitter usage and community resilience during Hurricane Isaac in 2012. They found significant positive correlations between Twitter usage density and resilience indicators, confirming that communities with higher resilience characterized by better social-ecological conditions tend to have higher Twitter usage. Resch et al. (2018) argue that classical disaster management methods have shortcomings in temporal and spatial resolution, and this can be improved by generating a new and unseen layer of information in near real-time using social media data. The proposed approach uses LDA for semantic information extraction combined with spatial and temporal analysis for hotspot detection.

Moreover, Fan et al. (2020) argue that social sensing complements physical sensing techniques to improve situational awareness of disturbances in the built environment and that effective and efficient disaster response and recovery requires reliable situational awareness of infrastructure disturbances and their social impacts. They proposed an integrated Textual-Visual-Geo framework for situational awareness using Twitter data. They used a graph-based approach to detect critical tweets, an image ranking algorithm based on the number of retweets, text content to select important images, and kernel density estimation to estimate the geographic extent of the disruption in the case of Houston during Hurricane Harvey in 2017.

In the context of social media data analysis during disasters in Germany, Fathi et al. (2020) introduced Virtual Operations Support Teams (VOSTs) as a new team for organizing intelligence-gathering effort recently established by the German Federal Agency for Technical Relief (THW). Their role is to improve situational awareness among decision-makers in disaster response. Their study analyzed the structural, procedural, and technical requirements of VOSTs for joint operations with emergency management agencies in terms of social media monitoring, information verification, and crisis mapping in practice. Netzel et al. (2021) analyzed Twitter communication about heavy precipitation events to improve future risk communication and disaster preparedness in Germany. The study was carried out from February 2019 until August 2019 and examined the time series, networks, and content of tweets regarding pluvial flooding. They found that warnings originating from established stakeholders were the most common type of message and emphasized that the role of these actors is crucial for continuous communication.

Furthermore, Gründer-Fahrer et al. (Gründer-Fahrer et al., 2018) analyzed topics and topical phases in German social media (Twitter and Facebook) communication during the flooding of 2013. They analyzed German social media communication's thematic and temporal structure using LDA Topic Modeling, sentiment analysis, and temporal clustering. Their findings revealed that Facebook content focuses on empathy and emotion. In contrast, Twitter is mainly used to share current and concrete information about the event and takes a more objective view of the event.

Although the above studies highlight the importance of using social media platforms and data for disaster management and communication, there is a shortage of studies that analyzes and leverages communities' collective knowledge to inform disaster resilience capacities.

2.3. 2021 floods in Germany

EM-DAT, the International Disaster Database, ranked the July 2021 flood in Germany as the 10th deadliest in Europe in the last 100 years (“EM-DAT,” 2022). A slow-moving large summer storm system named 'Bernd', whose size and moisture are attributed to climate change, resulted in high rainfall amounts -up to 150-200 mm within 48 h- (see Figure 1) and corresponding runoff peaks (Junghänel et al., 2021).

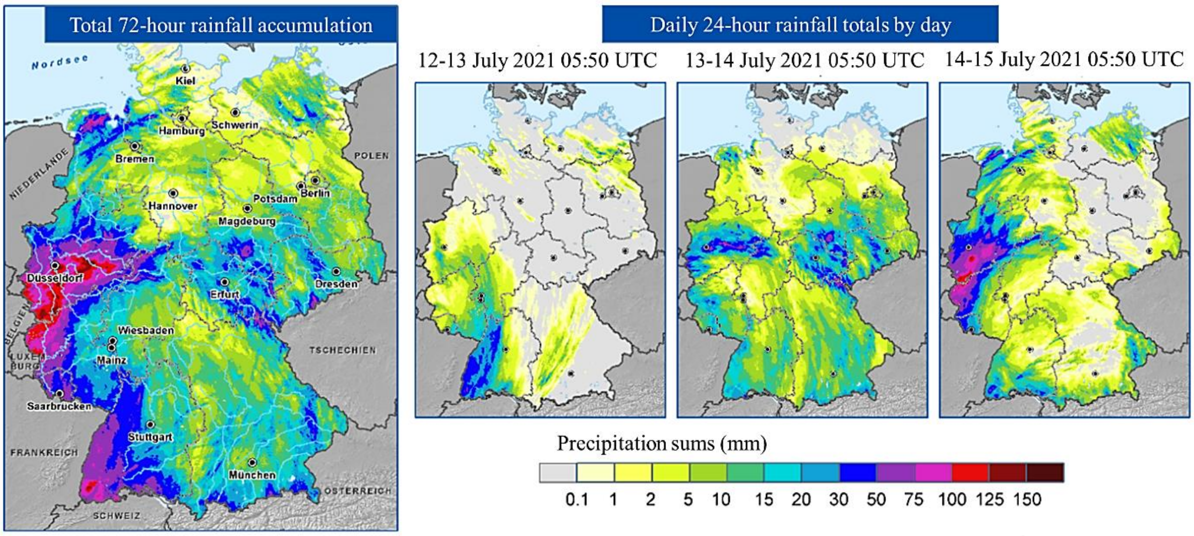


Figure 2: Torrential rains caused catastrophic flooding in Germany (especially in the western states) from July 12 to 18, 2021; modified from (Junghänel et al., 2021)

Although the affected federal states were Baden-Wuerttemberg, Bavaria, Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Saxony, Saxony-Anhalt, and Thuringia, the worst flooding occurred in the western states of Rhineland-Palatinate and North Rhine-Westphalia on the evening of July 14, and in Saxony and Bavaria in the south on July 17("EM-DAT," 2022; Fekete & Sandholz, 2021). On July 12, 2021, the European Flood Awareness System (EFAS) issued an extreme flood warning for Germany and Belgium and updated the weather situation in the following days. EFAS shares the information with national authorities responsible for disaster preparedness and response. These then forward the information and ensure the necessary measures are taken (European Parliament, 2021).

While riverine flooding is more common and minor pluvial flooding has occurred more frequently in recent years, pluvial flood damage on this scale was unusual. Most importantly, the high death toll was a surprise and a shock in an industrialized country that had never experienced such a high death toll and damage. Therefore, similar to other flood disasters in other countries, a public debate about responsibility and blame soon began, and crisis management came under criticism from the media and the public (Fekete, 2021). Following the constitution, which gives states the authority to enact laws relating to disaster crisis management, states enact their own laws. The various state laws thus result in differences among the states in command and control, training, and equipment (BMI, 2012). Against this backdrop, and to create better situational awareness, distributed problem-solving, and collective knowledge of capacities and issues related to the 2021 flood disaster, the following section explains the study approach to incorporate Twitter data and online surveys into the study of community resilience.

3. Data and Methods

The data in this study was collected through two sources: Twitter, Germany, from July 12 to 31, 2021, and an online survey conducted from September 1 to 21, 2021. Figure 3 illustrates an overview of the data collection process, pre-processing and analysis methods described in the following sub-sections.

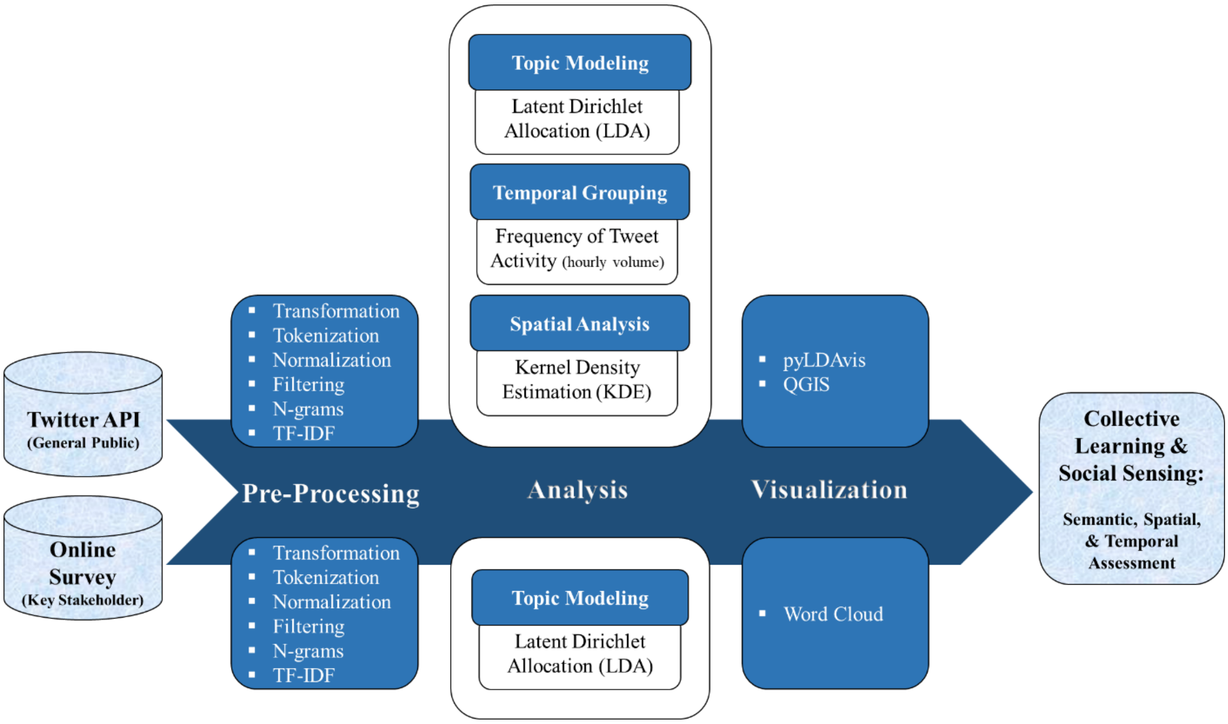


Figure 3: Methodological workflow

3.1. Twitter data collection and processing

3.1.1. Tweet collection

First, using the academic API (application programming interface) of the Twitter platform, we mined German social media (Germany as the predefined area) data from July 12 to the end of July 2021. To extract meaningful data on disaster-related tweets, we considered the hashtags listed in Table 1 before, during, and after the flood event. Each tweet includes the date of creation, the content, the username, and possibly geolocation information such as coordinates and locations of the tweet. The timing of the tweet was used to divide the data into pre-event/preparation (July 12-13, 2021), real-time event/immediate response (July 14-17, 2021), and post-event/short-term recovery (July 18-31, 2021) phases. To determine the location of the tweet, we queried "geo" (indicating the location the user tagged in the tweet if they provided one) and also "geo.place_id" (if present, this indicates that the tweet is associated with a location) (Laylavi et al., 2016; "Twitter Developer Platform," 2022). A total of 6640 tweets were retrieved, of which 1810 were geo-referenced.

Table 1: Hashtags set before, during, and after flooding events (near-real time)

Pre-Event (12-13 July 2021) Prevention and Preparedness	**Real-Time Event (14-17 July 2021) Immediate Disaster Response**	**Post-Event (18-31 July 2021) Disaster Recovery (Short-Term)**
Identification and signaling of flooding hazards and dissemination of disaster preparedness and early warning information at the national or regional level	Maintaining near real-time communication and information exchange for improved situational awareness in space and time (people as sensors)	Short-term measures addressing immediate needs (restoring critical infrastructure, mobilizing volunteers, emergency shelters, collecting donations, etc.) and discussing socio-political and scientific causes and responsibilities of an event
#Wetterwarnung (weather alert) #Unwetterwarnung (storm alert) #Starkregen (heavy rain) #Dauerregen (continues rain) #Extremwetter (extrem weather)	#Hochwasser (flood) #Flut (flood) #Hochwasserkatastrophe (flood disastre) #Flutkatastrophe (flood disaster) #Starkregen (heavy rain) #Unwetter (storm) #Feuerwehr (fire	#Hochwasser (flood) #Flut (flood) #Hochwasserkatastrophe (flood disastre) #Flutkatastrophe (flood disaster) #Starkregen (heavy rain) #Unwetter (storm) #Feuerwehr (fire

#Unwetter(storm) #Hochwasser (flood) #Feuerwehr (fire department) #Überflutungen(floods) #Flut (flood) #Überschwemmung (flooding)	department) #Überflutungen (flood) #Dauerregen (continous rain) #Überschwemmung (flooding) #Extremwetter (extrem weather) #Hochwasserhilfe (flood relief) #Klimawandel (climate change) #Fluthilfe (flood aid) #Fluthelfer (flood helper) #Helfer (helper) #Hochwasserhilfe (flood relief) #Spenden (donate) #Infrastruktur (infrastructure)	department) #Überflutungen (flood) #Dauerregen (continous rain) #Überschwemmung (flooding) #Extremwetter (extrem weather) #Hochwasserhilfe (flood relief) #Klimawandel (climate change) #Fluthilfe (flood aid) #Fluthelfer (flood helper) #Helfer (helper) #Hochwasserhilfe (flood relief) #Spenden (donate) #Infrastruktur (infrastructure)
110 geo-referenced tweets	**2830 tweets, including 683 geo-referenced tweets**	**3700 tweets, including 1017 geo-referenced tweets**

3.1.2. Twitter data pre-processing

We pre-processed the entire corpus from the data mining phase after deleting duplicates and translating (4842 tweets and 1729 geo-referenced tweets remained). Pre-processing is necessary to remove noisy data, increase data quality, and improve keyword generation and analysis results (Resch et al., 2018). The raw texts were cleaned by transforming the data (removing punctuation, emails, URL links, numbers, and emojis, and converting the text to lowercase), normalizing (using lemmatization, which creates the root form of inflected words), and filtering (deleting stop words such as 'the', 'on', etc.). N-grams (bi-gram and tri-gram) were used to find frequently occurring words in the document. Term frequency-inverse document frequency (TF-IDF) was used to assign a weight to each word based on word frequency to balance the importance of the word in the tweets and the corpus. The cleaned tweets were tokenized to convert them into words for further analysis (Zhou et al., 2021).

3.1.3. Spatial and temporal distribution of tweets

Human reactions, such as the frequency of communication on social media, are dynamic based on disruption situations. A burst in the frequency of tweets may indicate a change in the situation or a significant impact of the disruption on people (Fan et al., 2020). Since each tweet is associated with the time of its creation, we calculated the hourly volume of tweets (frequency of tweet activity). This can show whether the temporality of tweets correlates with the flooding situation's dynamics.

Although people rarely disclose their location on public platforms, every tweet is associated with a location. The distribution of geolocated or geo-tagged tweets can estimate the locations and extent of disturbances and provide location information. The more geo-tagged tweets posted at the same location, the greater the damage and the stronger the impact of the disruption (Fan et al., 2020; Kryvasheyeu et al., 2016). To estimate the extent of the disturbance based on the spatial distribution and density of tweets, we performed Kernel Density Estimation (KDE) approach through the heatmap analysis tool in QGIS 3.24.2. Based on the method proposed by (Rizzatti et al., 2020), we calculated the search radius for obtained tweets before, during, and after the event. In each case, we applied KDE with a radius of 136, 140, and 151 kilometers and a pixel size of 500 meters. Then, the quartic Kernel function was chosen, as it is characterized by giving more weight to points closer than those further away. The heat map was finally created, which is shown in the next section.

3.1.4. Semantic (textual) information extraction from Twitter data

Topic Modeling is one of the most powerful techniques in text mining, discovering latent data, and finding relationships between data and text documents, in which LDA is one of the most popular in this field (Jelodar et al., 2019). LDA is a generative probabilistic model based on the concept that a set of sentences or documents contains certain topics. A topic refers to a group of words with similar or closely related meanings under certain probabilities. If the author of the document (tweet) is a person, these topics reflect the perspective and vocabulary of that person. Therefore, in this study, LDA was applied to the final set of cleaned tweets using the Gensim library to analyze the unstructured textual information from the tweets and identify the flooding-related topics before, during, and after the floodings.

LDA models document D as a mixture of K latent topics, and each topic describes a multinomial distribution over a W word (Huang et al., 2018). Equation 1 shows how the probability of a corpus is obtained (Blei et al., 2003).

$$(1) \qquad p(D \mid \alpha, \beta) = \prod_{d=1}^{M} \int p(\theta_d \mid \alpha) \cdot \left(\prod_{n=1}^{N_d} \sum_{z_{dn}} p(z_{dn} \mid \theta_d) p(w_{dn} \mid z_{dn}, \beta) \right) d\theta_d$$

Figure 4 represents the graphical model of the LDA. The outer box indicates the documents, while the inner box represents the repeated selection of topics and words within a document.

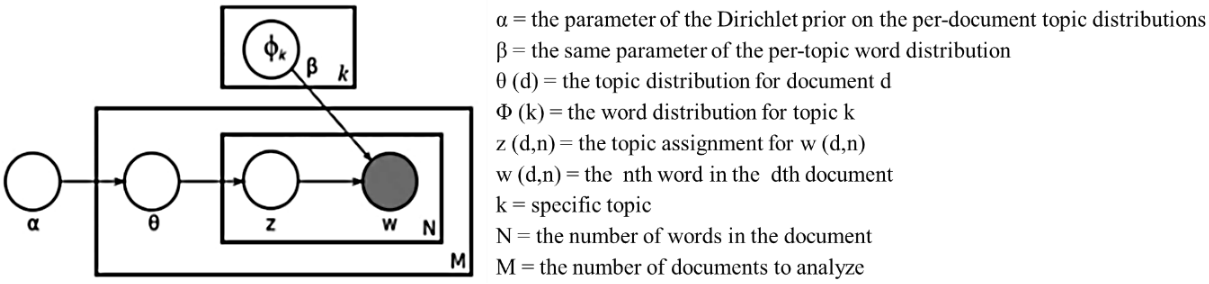


Figure 4: Graphical model representation of LDA; Source: (Blei, et al. 2003)

For validation of the model and to provide a convenient way to measure how good a particular topic model is, the perplexity and coherence measures are applied. The perplexity score is intuitively based on the degree of surprise a trained model experiences when confronted with unfamiliar documents after the learning phase. Lower perplexity indicates a better generalization ability of the model (Blei et al., 2003). On the other hand, the coherence value reflects the correspondence between numerical scores and users' perception of the quality of topic models (Mimno et al., 2011). The higher the topic coherence, the more interpretable the topic is to humans (Gründer-Fahrer et al., 2018).

Finally, pyLDAvis was used to visualize the results, which was developed to help users interpret the topics in a topic model fitted to a textual corpus of data in an interactive web-based visualization (Sievert & Shirley, 2014). Compared to traditional clustering techniques, where each tweet can only belong to a single topic, an advantage of pyLDAvis is that a word can be clustered to different topics. For example, the word 'water-level' may appear in a context related to situational information or emergency operation. In this case, it can better represent the nature of the language (Sievert & Shirley, 2014; Zhou et al., 2021). The topics extracted from the LDA model reflect the different aspects of the event (Huang et al., 2018; Zhou et al., 2021) from a crowds perspective. Thus, we examined the composition of words in these automatically generated topics for each phase and manually assigned semantic labels in light of the authors' domain knowledge and their consensus (Gründer-Fahrer et al., 2018).

3.2. Online survey data collection and processing

The second data source used in this study was an online survey conducted by (Fekete, 2021) to better understand the insights and perceptions of disaster responders involved in 2021 flooding regarding flood crisis management issues and capacities. The online survey allows for open and broad participation while maintaining anonymity on such sensitive topics where organizations have limitations in sharing information. Other advantages of online surveys include independence from respondents' local availability and time and cost savings (Nimrod, 2014). The online survey was conducted using the SoSciSurvey online tool and was divided into 31 questions, including 24 closed questions and seven open questions, with 2264 participants. The preliminary analysis of the survey was published by (Fekete, 2021). However, in this study, an in-depth analysis of the open-response texts is conducted to potentially uncover additional themes, suggestions, concerns, positive experiences, and areas for improvement by capturing direct open opinions and expressions. 911 respondents used the open response fields, and 37,400 words of text (approximately 94 pages) were collected. For analysis, each question's text was considered a separate corpus. After pre-processing and cleaning the data, the LDA method for Topic Modeling was used and visualized by word cloud.

The analyzed data from these two sources, Twitter and the online survey, were ultimately compiled to reflect the wisdom of crowds and collective intelligence regarding flood resilience, which is discussed in more detail in the following section.

4. Results

4.1. Spatio-temporal characteristics of the flood-related tweets

By examining the spatio-temporal distribution of posts on social media, we can get an overview of citizen behavior and reactions to a disaster event. Figure 5 shows the temporal pattern of flood-related tweets in different disaster phases. Despite the extreme flood warnings issued by the EFAS as well as the extreme rainfall warnings announced by the German Weather Service (DWD) for the eastern and southern federal states on television and radio from July 12, only a few tweets were posted on the subject of flooding before July 14 (see Figure 5). Nevertheless, the spatial distribution of flood-related tweets shows that most tweets originated from these regions (see Figure 6).

Between July 14 and 17 (during the disaster), the number of tweets increased dramatically, showing four peaks, with the first peak occurring between 12:00 and 20:00 on July 14, the second starting at 3:00 on July 15, the third starting between 7:00 and 21:00 on July 16, and the last peak occurring between 17:00 and 20:00 on July 17. The heavy rainfall on July 14 and 15 caused enormous flash floods (evening of July 14 to the early morning of July 15) with water levels up to more than eight meters in parts of North Rhine-Westphalia (NW) and Rhineland-Palatinate (RP). In RP, the districts of Ahrweiler and Trier-Saarburg were severely affected. Indeed, the "flood on the Ahr" shaped the "media memory" (Broemme, 2022). On July 16, for an extended period during the day from 8:00 to 20:00, tweets about the flood were posted reflecting the adverse effects of the flood and the significant impact of the disruption on people, roads, transportation, infrastructure, etc. Finally, the last peak occurred on July 17, indicating another flood in southern Bavaria (BY). Several roads in the region were closed, and train traffic was partially disrupted.

From July 18 (after the disaster), the temporal pattern of tweets remained the same for about 5 days. But as time passed, the number of tweets about the flooding gradually decreased until the end of the month.

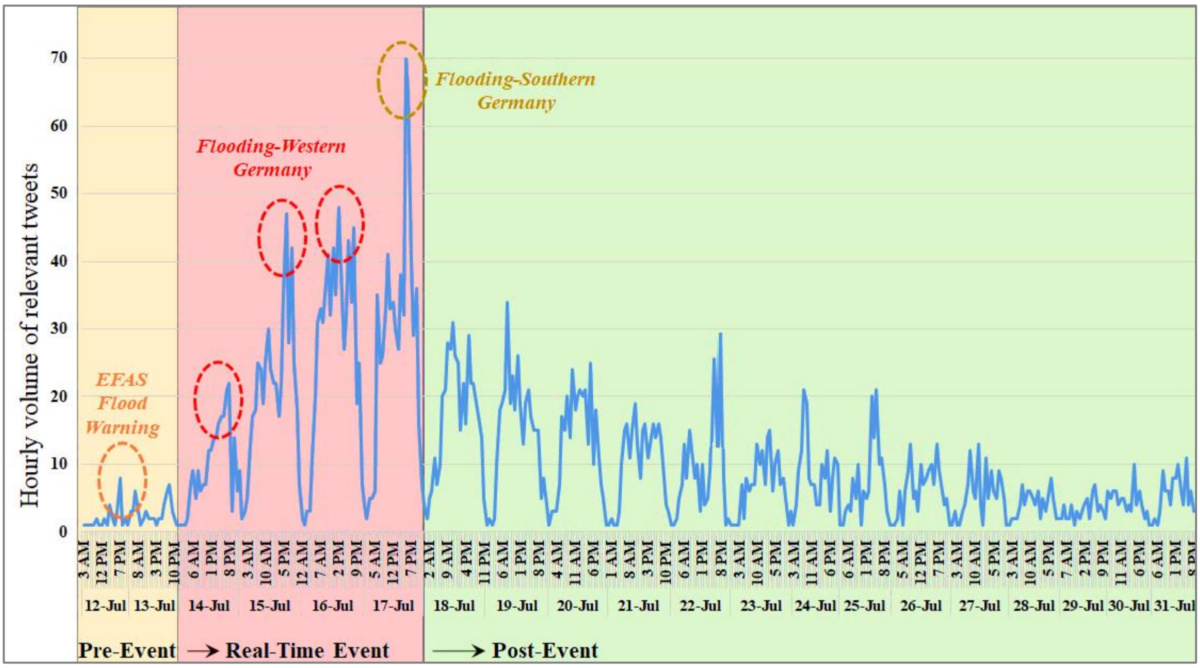


Figure 5: Hourly volume of flood-related tweets from 12 to July 31, 2021

From the hotpot map in Figure 6, it can be seen that most tweets in the pre-event phase were posted from NW, BY, BW, and then RP and Berlin (BB) about weather conditions and heavy rain warnings. In the real-time flooding phase, the highest density of tweets can be seen in NW and RP, as these areas were the most affected. In the post-event phase, it can be seen that the kernel density pattern expands to BY and BB, showing the impact of flooding in the south and also in the capital city with increasing the number of corresponding tweets. Although BB was slightly affected by the pluvial flooding, tweets were mainly about humanitarian aid, risk governance, and climate adaptation (see section 4.2.3).

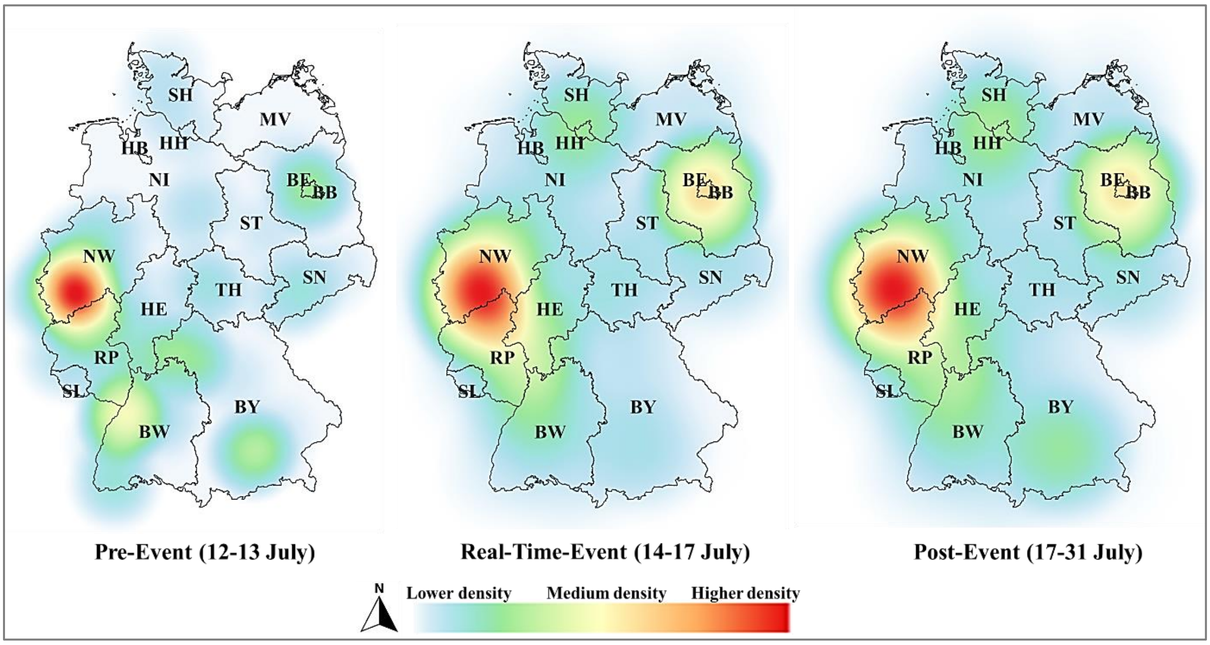


Figure 6: Spatial distribution of flood-related tweets (Kernel density) in Germany at the state level (the more reddish the color, the higher the density of tweets)

4.2. Content (textual) analysis of social media and online survey

After pre-processing the relevant tweets in the three disaster phases (pre-event, real-time, and post-event (short-term)), LDA was used to analyze the content of tweets in these periods, as it can be assumed that users send different categories of messages in the different disaster phases. LDA was also applied to the survey results indicated in the following subsections.

4.2.1. Pre-event Topic Modeling

In the pre-event phase (July 12-13), the optimal number of latent topics (k) based on perplexity (-6.43) and coherence (0.41) scores was 10. The most frequent terms were 'storm', 'heavy rain', 'climate crisis', 'rain', 'warn', 'fire-brigade', 'flood', 'extreme', 'weather', 'summer', 'ready'. The generated topics were visualized with pyLDAvis (Figure 7). Each bubble on the left side of the diagram represents a topic. The larger the bubble, the more prevalent the topic. A good topic model will have fairly large, non-overlapping bubbles scattered across the diagram rather than concentrated in one quadrant. By hovering over one of the bubbles, the words and bars on the right side are updated. These words are the salient keywords that make up the selected topic. For example, the selected topic in Figure 7 is Topic 1, represented by the words on the right side of the figure.

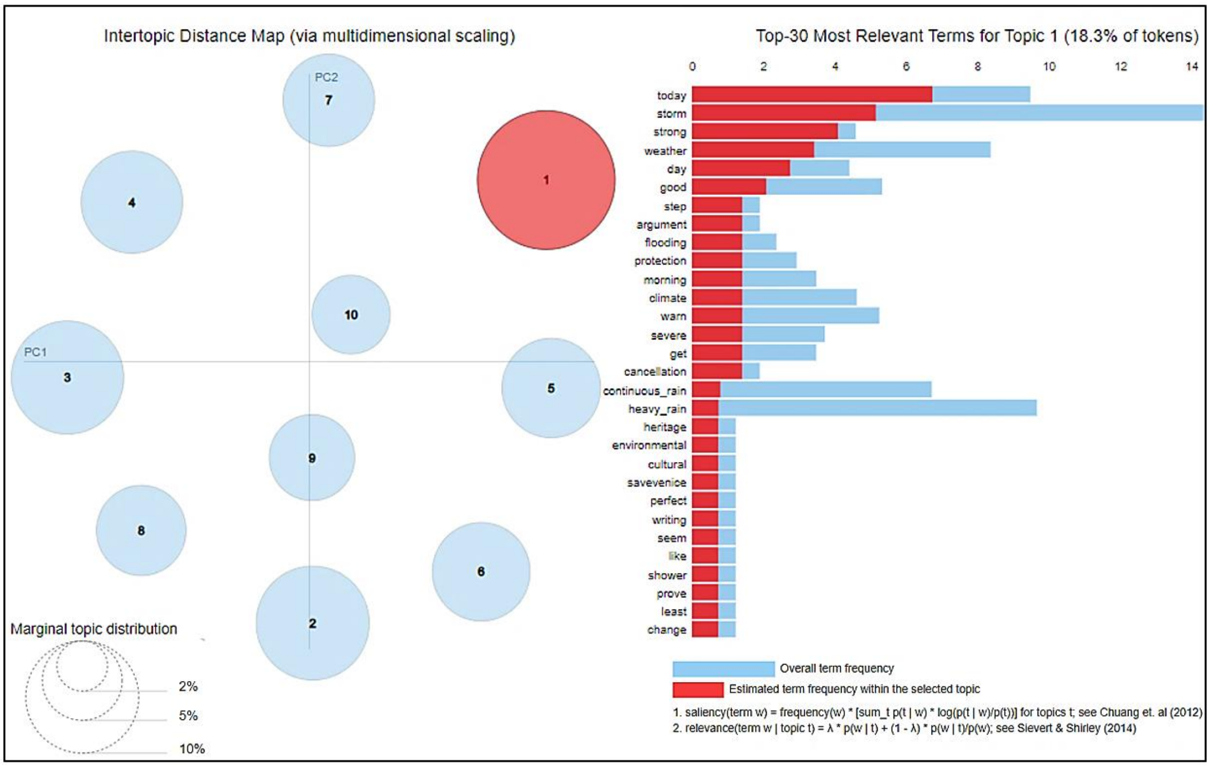


Figure 7: An example of visualization of Topic clusters and top 30 words for Topic 1, pre-event phase

The top 10 keywords contributing to this phase in different topics were 0.043*"flood" + 0.034*"storm" + 0.018*"rain" + 0.018*"fire_brigade" + "0.018*"extreme" + 0.018*"weather" + 0.018*"warn" + 0.009*"continuous-rain" + "0.009*"want" + 0.009*"severe"', where the weight reflects how important a keyword is to this theme. Using these keywords in each topic, we identified the thematic topics and began coding. Accordingly, Table 2 shows the most representative topics, including warning, early action, protective measures, event tracking, climate change-oriented information, disbelief in flood probability, and local emergency preparedness.

Table 2: Pre-event Topic Modeling, with examples of contributing keywords and representative text

Pre-event Topics (12-13 July 2021)	Example of contributing keywords	Example of representative Tweets
Warning	Warn, continuous-rain, heavy-rain, weather, severe, morning, high, etc.	'Heavy rain has been announced for Bonn and the region today', 'German weather service is again warning of heavy rain within three days, liters per square meter can fall in some places - there is a risk of small rivers and dams', 'severe weather warning strong flooding in the west, beware of the cellar and street'
Early action and protective measures	Cellar, precaution, soil, pitchfork, rain, finish, etc.	'And in Berlin even the cafés at the port of urban Vivantes Klinikum Kreuzberg are now being flooded, 4-fold coffee price and music to run away ', 'as soon as I get home I will poke holes in the lawn with a pitchfork so that more water can seep away a compacted soil is poison for heavy rain'
Predicting local situations and reflecting on lessons learned from past events	Protection, prepare, attention, significant, organize, etc.	'With a few exceptions, we were always lucky here. The last flood was Whitsun. Neighbors who live right on the edge of the field have now built small flood walls in the garden', 'we support the thw Ortsverband Mayen as well as the construction depot of the city together we were able to fill hundreds of sandbags and send them to the citizens of Mayen'
Event tracking	Today, water-level, threaten, Cologne, Rhein, significantly, day, etc.	'flood in the rhine', 'heavy rain Remscheid NW', 'good morning Jenny is the humidity so high where you are too there is supposed to be a storm with heavy rain today what is the situation in your region'

Climate change-related information	Climate-change, crisis, severe, storm, summer, etc.	‘climate crisis is now’, ‘climate crisis has now uprooted the system for our children and grandchildren everything is in it. it starts here we grow beyond ourselves’
Disbelief in the likelihood of flooding	Lie, sometimes, wrong, may, summer, DWD, etc.	‘yes there is significantly more water in the rhine but the flood protection wall is far from being reached’, ‘still waiting for the announced 150-200 liters per square meter here, not happening here in Düsseldorf, despite all the warnings, the DWD was wrong’
Local emergency service preparedness	Fire-brigade, blue light, ready, people, build, etc.	‘we are ready’, ‘heavy rain is announced today for Bonn and the region. Take precautions like us and pay attention to the weather and warning reports’

4.2.2. Real-time event Topic Modeling

The period between July 14 and 17 was considered the real-time event phase for the states of NW and RP. As shown in Section 4.1, the temporal analysis revealed a large number of tweets related to the flood event, with a high level of posting activity compared to the other two time periods. The spatial pattern also showed that most tweets originated from the affected states. This highlights a significant temporal correlation between flood occurrence and social media activity, implying that situational information about the disruptions tends to be generated by locals and nearby communities affected by the disruptions.

LDA analysis for this phase was conducted with the optimal number of latent topics (30) based on perplexity (-7.87) and coherence (0.45) scores. The top 10 keywords contributing to this phase from different topics were 0.211*"help" + 0.245*"climate-change" + 0.151*"flood_disaster" + 0.132*"donate" + 0.127*"flood"+ 0.137*"water-level" + 0.129*"catastrophe" + 0.091*"people" + 0.082*"need" + 0.080*"infrastructure".

Table 3 shows the most relevant labeled themes extracted from these 30 clusters by analyzing the keywords in each topic. The themes are oriented around warning systems, situational information, communication with fellows, disaster mortality, affected people and their assets, damage to infrastructure, essential services and facilities, cascading effects or compounding risks, rescue, and relief oriented, humanitarian aid, donation and campaigns, sentiments, critique to politicians, and preventive measures.

Table 3: Real-time event Topic Modeling, with examples of contributing keywords and representative text

Real-Time Event Topics (14-17 July 2021)	**Example of contributing keywords**	**Example of representative Tweets**
Questioning warning system and strategy for risk communication	System, protection, situation, time, warning, local, authority, etc.	‘we need a risk communication strategy and weather disaster awareness campaigns’, ‘experts said the European Flood Awareness System (EFAS) issued an extreme flood warning earlier this week. passed on the warning to local authorities, who should have been responsible for organizing any necessary evacuations’, ‘people died because they were not warned effectively on time, system failure of disaster protection’
Posting situational and local information	Water level, Rhein, Ahr, time, sandbag, street, rescue-worker, dick, etc.	‘plus all the water from Moselle and Ahr. Rhine is already at 8 m’, ‘the good news is that the water level is now slowly sinking and the dam is stable and has not moved a millimeter. the bad news is that the number of deaths has unfortunately increased. the evacuation is in high water’, rescue workers secure the dike with sandbags with current status on the deployment in the east park settlement of Düsseldorf’
Communication with fellows to exchange information and help	Thank, greeting, friend, help, news, internet, cellar, well, see, etc.	‘girlfriend sits in America, sees the pictures from the Ahr valley and cannot reach her mother in Bad Neuenahr, who is in the old people's home there. anyone knows what to do there.’, ‘thanks to everyone who's contacted me to make sure we're ok here.’, ‘if someone in Bochum Langendreer still has a full cellar or something I could help out with a pump and hoses write to me if necessary’
Reporting on disaster mortality and missing people	Miss, dead, still-missing, hundred, victim, people-die, etc.	In Schuld, in the Ahrweiler district, 70 people are missing. Seventy. The small town on the Ahr has 660 inhabitants’, ‘number of dead on the Ahr at 90’, ‘the Lebenshilfe is around the corner, there were 11 disabled people who couldn't get out and called for help..., at some point it got quiet’, ‘as of this morning, the Koblenz police have registered more than 90 people who died in the flood disaster in the greater Ahrweiler area’
Reporting on people and assets affected	Car, garage, cellar, house, all, animal,	‘As of now, two friends of mine have lost everything - except their lives. the restaurant we ate at in early June no longer exists’, ‘severe flooding has it NW Germany overnight,

	income, business, relocate, etc.	six houses have collapsed and other houses are at risk of being washed', 'Vanessa lives in Ahrweiler, her brand new Audi is damaged she lost all.'
Reporting on damage to infrastructure and disruption of basic services	Infrastructure, road, bridge, break, failure, network, power, highway, etc.	'the Nepomuk Bridge (built-in 1723) no longer stands. Just like most bridges in the Ahrtal', 'All good, no network, no water. Get in touch, 'All bridges destroyed for 35 km. Ahrweiler district in Germany is like a theater of war', 'many gas lines have completely ruptured, the apartments remain cold even in autumn and winter', 'highways attacked by heavy rain'
Provision of essential services and facilities	Electricity, network, clothes, food, hygiene, shelter, evacuation, etc.	'Food, drinking water, hygiene items, clothing, blankets, and dog food can be picked up at the Kalenborn volunteer fire brigade station', 'we currently also have to evacuate the hospital around patients are already out by helicopter and the rescue workers are taking lying patients to the Trier clinics', 'in Hagen authorities urge residents of most flood endangered areas in the city center and near rivers to evacuate to emergency shelters.'
Reporting cascading effects and compounding risks	Landslide, corona, pandemic, combination, transport, bus, late, dam, etc.	'the consequences of the coincidence of corona and the flood disaster like in Ahrweiler would certainly have been devastating. unfortunately, often we think too short-sighted so that often only luck saves us from worse damage', 'from corona crisis to the flood disaster people should learn to live with nature and not act as if we were omnipotent we can solve climate change with climate protection or we will end up deeper in the climate crisis.'
Reporting the services of emergency organizations and helpers	Helper, relief, rescue-worker, siren, THW, fire-brigade, deploy, etc.	'German army helping out with the flooding effective areas', 'rescue often only possible from the air', 'exactly that is the point, if it is clear that the catchment area of the Kyll/Ahr will be flooded, then you can organize deployment, bring forces and equipment to the site', 'emergency services deployed according to the blue lights and sirens, a mega-caravan is driving over the autobahn in the direction of Ahrweiler'
Exchange information about humanitarian aid and crowdfunding	Flood-aid, donation-kind, fundraise, help, campaign, etc.	There will probably be a lot of packs available for purchase next week. The proceeds go to winegrowers from the Ahr Valley who have lost a lot or even everything. Buy wine and do good with it', 'donate whatever you can', I just donated money for those affected by the flood disaster, if you are still looking for a fundraising campaign, you will find here what you are looking for'
Sharing disaster-related sentiments	Unbelievable, failure, surprise, sad, mourning, empathy, etc.	'Wuppertal, Hagen, Hohenlimburg, the Voreifel, the Ahr Valley and and and...I am speechless and sad', 'I am horrified by these pictures and I feel very sorry for you. It's my district town and I know many places on the Ahr from hiking. Isn't there the possibility of a call for donations only for Ahrweiler and Guilt? Think of everyone in the Ahr valley.', 'together we are strong, let's join forces for the best possible help'
Criticism of Politicians	Minister, chancellor, cdu, green, laugh, unbureaucratic, election, etc.	'it is terrible that a prime minister is laughing at more than 100 deaths', 'German wine ambassadors visited Ahr Valley only recently that now disappeared in floods never seen before. thank you for your solidarity.', 'it disgusts me how heavy flood wave rain is being cannibalized for the election campaign by all political sides','government was warned days before the catastrophe of the flood that monumental failure was a monumental failure'
Suggesting preventive measures	Climate- change, soil, surface seal, wind-farm, support, cost, insurance, etc.	'I think now it is time to take out elementary damage insurance. climate change is here.', 'anyone who calls for the expansion of wind farms closer to settlements after the flood should remember that every single system comes with a reinforced concrete foundation plus driveways a wind farm so extensive soil sealing means we are currently seeing the consequences', 'the sealed areas of plots of land that were washed away by the flood did not receive a building permit'

4.2.3. Post-event Topic Modeling

This study considers the period between July 18 and 31, the short-term post-event phase. Temporal analysis in Figure 5 shows that the tweet activity pattern remained the same for about five days, and the number of tweets about the flooding gradually decreased by the end of the month. According to spatial analysis, most tweets are generated from two states, NW and BY.

LDA analysis for this phase was conducted with the optimal number of latent topics (30) based on perplexity (-8.28) and coherence (0.51) scores. The top 10 keywords contributing to this phase from different topics were 0.235*"flood-disaster" + 0.161*"today" + 0.132*"climate-change" + 0.129*"help" + 0.122*"donate"+ 0.112*"fire-brigade" + 0.100*"helper" + 0.091*"home" + 0.089*"death" + 0.081*"old".

Table 4 shows the most relevant labeled themes extracted from these 30 clusters. The topics are oriented around crowdfunding and humanitarian assistance, social and financial support, sentiments for victims, needed utilities and services, infrastructure reconstruction, emergency management, information and communication, lack of security and appreciation of helpers, environmental change, etc. The data-driven topics show community discussions about socio-political and climate-related causes, collecting donations, on-the-ground assistance, information provision, and communication, as well as suggestion to improve risk governance through climate policymaking and organizational innovations.

Table 4: Post-event Topic Modeling, with examples of contributing keywords and representative text

Real-Time Event Topics (18-31 July 2021)	Example of contributing keywords	Example of representative Tweets
Exchange information on crowdfunding & humanitarian assistance	Cloths, money, help, aid, support, fundraise, campaign, charity, etc.	'parts of Germany have been hit by floods and lost everything today I was able to donate two bags full of clothes several hygiene articles and water to them', 'The flood relief fundraising campaign for long-distance calls via flood catastrophe continues to this day', 'aid from the USA in the flood area the aid organization aviation without borders from Frankfurt is working on the Ahrwir holdings'
Suggesting social and financial support	Social, protection, aid-organization, business, significant, government state, etc.	'German government has made available million euros to help rebuild communities affected by the flood insurance companies will foot around billion in claims', 'we will donate the sum on your receipt and all other income from our markets that arose during this hour of donation to the campaign Deutschland Hilft alliance of aid organizations provides emergency aid for the people of the flood wave Ahrtal'
Sharing disaster-related sentiments	Victims, empathy, sad, solidarity, angry, help, people, fail, responsible, government, etc.	'Germany is a wealthy country and has the resources for proper flood protection and warning systems the death toll did not need to be so high that is why people are angry', 'great action under the label Flutwein, bottles of wine from the Ahr are sold to support the rebuilding of the regional flood relief flood trip flood disaster solidarity'
Communicating for the provision of utilities and services	Water, food, power, doctor, population, hospital, relief, service, emergency, etc.	'a friend from the Ahr valley is telling me that freshwater canisters and tanks will be needed in the area for the long term', 'flood relief for animals I have just donated some food to the vet', 'Emergency doctors from Badneuenahr picked up spontaneously shortly after this idyllic location, we went down to the Ahr valley', 'station in Ahrweiler the gastro grill station is unloaded a lot of good food with it'
Reporting on rebuilding infrastructure and green investment	Infrastructure, climate, investment, state, network, measure, bridge, etc.	'critical infrastructure such as sewage system is to be rebuilt as soon as possible', 'anyone who still thinks that investments in climate and environmental neutrality are too expensive has serious logic deficits or is part of coal lobby', I think that a warn app like Nina should work until the disaster occurs, even if there is no electricity afterward, including internet and other infrastructure', 'one suspects that the reconstruction of the destroyed bridge and infrastructure can easily take up to years'
Appreciation of emergency organizations and helpers	Flood-disaster, warning, volunteer, affect, thank-helper, helper, voluntary, THW, fire-brigade, etc.	'thank you thank you to the many helpers who tirelessly support the victims of the flood disaster', 'heroes wear flecktarn the soldiers of the Bundeswehr do great things in the disaster areas and thanks to the whole country to the rest of the helpers', 'returning from the USA completely different and more extensive warning infrastructure compared to Germany warnings on all channels'
Exchange information and communication	Inform, call, hour, report, local, area, sort, center, emergency, etc.	'please share and pass on official and secure information on the situation in the Ahrweiler crisis area is now also available on flood Ahr info tweet', 'does anyone have information about the situation in Kreuzbergahr', 'the underground car park in Gutbiesdorf is currently full of water. The neighbors walk around the houses and ask for the car to be driven out'
Lack of security and appreciation of helpers	Police, lateral_thinker, attack, help, THW, garbage, etc.	'lateral thinkers in flood areas, helpers are insulted and pelted with garbage', 'Violence against voluntary helpers like sick someone has to be around people who sacrifice their free time to help others to do something like that, so-called lateral thinkers and imitators you have been so stupid', 'THW employees insulted in the crisis area and pelted with garbage'
Highlighting climate change impacts	climate-change, wash, damage, everything, danger, temperature, cause, etc.	massive damage to buildings and infrastructure in Dernau road bridge in the middle broken railway tracks washed out broken down or no longer available', 'first NW and RP and now SN and BY something like that often happens with climate change and it gets worse'
Highlighting the need for anticipatory environmental actions	Climate-change, action, prevent, car, change, bicycle, urgently-need, etc.	'who is supposed to pay for today's system of waste of resources with environmental destruction and climate change', 'your car taxes energy taxes are not even enough for the expansion and maintenance of the infrastructure and the encounter with the environment and damage to health, that's why everyone pays for it, even those who do not own a car'
Highlighting the need for climate-related policies and behavioral changes	Climate, policy, case, late, prevent, amount, hope, question, discussion, etc.	'good comment from about the climate chancellor Merkel who understands the huge dangers of climate change and has made her policy almost exclusively for big cars, big corporations and big farms', 'new fossil fuel infrastructure is fire accelerator for climate crisis & considerable investment risk, we greens are not demanding new long term terminals stop of green hydrogen infrastructure & renewable to full gas in the crisis edges'

Highlighting the need for climate adaptation	Future, often, drought, flood, digital, learn, measure, state, green, prevent, development, etc.	‘one should also adapt dams to current situations and climate change in the future there will probably be more drought summers but also such heavy rain events not only will such floods occur every year’, ‘the state budget is relieved enormously if, for example, as is currently the case, it is a matter of reconstruction and immediate relief measures due to the flood disaster’
Highlighting the need for climate-related transformational measures	Policy, environment, system, organization, modern, investment, technology, etc.	‘what is our path as a country in terms of climate policy how do we continue with digitization and renewal of the infrastructure’, ‘through an organizational separation of infrastructure and operations, the federal government can concentrate fully on the provision and modernization of the infrastructure’, ‘organizational innovation to prevent the diffusion of responsibility such as unclear responsibilities between federal states’, ‘space technology stands for technical advancement climate change is fought through intelligent technical solutions’

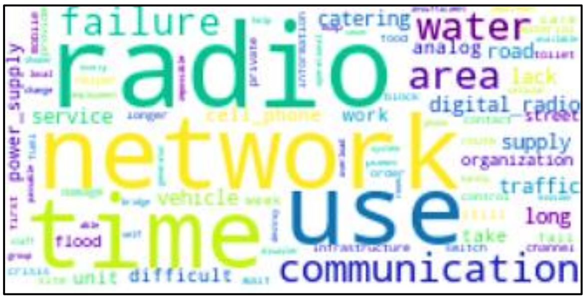
4.2.4. Online survey Topic Modeling

LDA analysis was also performed for the survey. Considering the perplexity and coherence measures presented in Table 5, the optimal number of latent topics for each corpus (survey questions) happened to be K=3. According to Fekete (2021), although operational organizations and responders (the group surveyed) are on the front lines of crisis management, few studies addressed their perceptions of problems and capacities. Table 5, therefore, reflects their critical statements in the open-ended questions. Instead of the pyLDAvis visualization, the conventional presentation of the results (10 contributing terms and their weights) is shown. The word cloud also shows the most frequent words under each question.

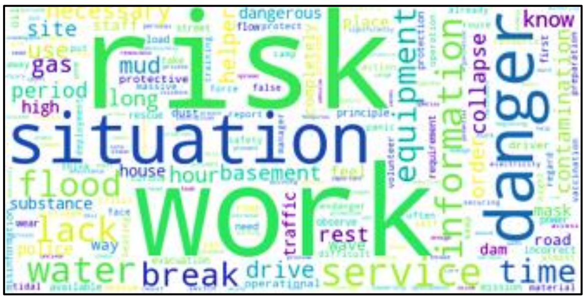
Table 5: Topic Modeling for seven open-ended questions of the online survey of the responders

Label	10 contributing terms (codes) and assigned weights
Q1: In which subject areas did you have problems? [coherence score: 0.53; perplexity: -7.40]	
Problem with command and control structure	0.014*"order"+ 0.014*"command"+ 0.014*"deployment"+ 0.013*"control-center"+ '0.012*"time"+ 0.011*"assignment"+ 0.011*"change"+ 0.011*"leadership" +0.010*"structure"+ 0.010*"operation"
Ineffective communication and information dissemination problems	0.035*"bad_information"+ 0.026*"structure"+ 0.021*"long"+ 0.017*"change"+ 0.016*"force" + 0.016*"staff"+ 0.015*"frequent"+ 0.014*"take"+ 0.013*"time"+ 0.012*"poor"
Insufficient provision of equipment, tools, and infrastructure	0.023*"assignment"+ 0.019*"equipment"+ 0.017*"thing"+ 0.016*"personnel"+ '0.016*"area" + 0.015*"digital"+ 0.014*"help"+ 0.014*"lack"+ 0.013*"pump"+ "0.013*"protective"

Label	10 contributing terms (codes) and assigned weights
Q2: Has an infrastructure failure affected you during operations? [coherence score: 0.50; perplexity: -6.57]	
Lack of communication and services and tools	0.020*"digital-radio"+ 0.018*"network"+ 0.015*"map"+ 0.012*"mobile"+ 0.011*"system"+ 0.010*"fail"+ 0.010*"cell-phone"+ 0.010*"area"+ 0.010*"communication"+ 0.010*"mobile"
Transportation issues	0.020*"road"+ 0.016*"traffic"+ 0.013*"vehicle"+ 0.012*"street"+ 0.012*"block"+ 0.011*"access"+ 0.011*"passable"+ 0.010*"difficult"+ 0.010*"fuel"+ 0.010*"lack"
Lack of basic utilities and facilities	0.020*"catering"+ 0.018*"failure"+ 0.015*"food"+ 0.014*"lack"+ 0.012*"toilet"+ 0.011*"area"+ 0.010*"water"+ 0.010*"power-supply"+ 0.009*"local"+ 0.009*"care"



Q3: Were there any situations in which you felt at risk? [coherence score: 0.53; perplexity: -6.86]	
The heavy workload for flood responders	0.017*"work"+ 0.012*"situation"+ 0.011*"equipment"+ 0.011*"service"+ 0.010*"lack"+ 0.010*" protective"+ 0.009*"load"+ 0.009*"rest"+ 0.007*"collapse"+ 0.007*"long"
High level of situational risk in affected areas	0.013*"risk"+ 0.012*"flood"+ 0.010*"dangerous"+ 0.010*"mud" + 0.009*"electricity"+ 0.009*"basement"+ 0.008*"oil"+ 0.008*"contamination"+ 0.008*"dam"+ 0.007*"driver"
Lack of personal safety and security	0.010*"danger"+ 0.008*"police"+ 0.008*"wear"+ 0.008*"mud"+ 0.007*"protect"+ 0.007*"camp"+ 0.007*"mask"+ 0.007*"access"+ 0.007*"panic"+ 0.006*"misinformation"



Q4: Were there aspects of your assignment that you found particularly positive? [coherence 0.46; perplexity: -6.21]	
Good level of collective action and community solidarity	0.075*"cooperation"+ 0.050*"aid-organization"+ 0.041*"helper"+ 0.023*"collaboration"+ 0.022*"volunteer"+ 0.021*"mission"+ 0.019*"willingness-help"+ 0.018*"merge"+ 0.018*"support"+ 0.017*"encouragement"
Good level of Social cohesion and bounded community	0.167*"cohesion"+ 0.079*"cooperation"+ 0.040*"helper"+ 0.036*"organization"+ 0.035*"support"+ 0.034*"work"+ 0.034*"camaraderie"+ 0.028*"regardless"+ 0.020*"team"+ 0.019*"helpfulness"
Care of society for the physical and social well-being of helpers	0.065*"gratitude"+ 0.046*"support"+ 0.044*"food"+ 0.025*"courteous"+ 0.021*"great"+ 0.020*"help" + 0.020*"provide"+ 0.019*"concern"+ 0.018*"care"+ 0.017*"catering"

Q5: In what areas do you think improvements are needed so that volunteers return from their assignments more satisfied? [coherence score: 0.41; perplexity: -7.02]	
Improving coordination and management	0.014*"training"+ 0.012*"management"+ 0.010*"leadership"+ 0.010*"staff"+ 0.009*"vehicle"+ 0.009*"coordination"+ 0.009*"train"+ 0.008*"communication"+ 0.007*"structure"+ 0.007*"organization"
Improving community and stakeholder knowledge	0.010*"helper"+ 0.009*"volunteer"+ 0.008*"problem"+ 0.008*"deployment"+ 0.007*"local"+ 0.006*"official" +

	0.006*"knowledge"+ 0.006*"preparation"+ 0.006*"training"+ 0.006*"information"
Improving disaster preparedness and planning	0.011*"exchange"+ 0.009*"deploy"+ 0.008*"equipment"+ 0.008*"train"+ 0.008*"prepare"+ 0.007*"organization"+ 0.007*"spontaneous-helper"+ 0.007*"material"+ 0.007*"preparation"+ 0.006*"alarm"

Q6: What do you expect from the people? [coherence score: 0.58; perplexity: -7.10]

Improving knowledge, skill, and preparation for disasters	0.020*"understanding"+ 0.014*"task"+ 0.011*"affect"+ 0.010*"knowledge"+ 0.010*"local" + 0.009*"preparation"+ 0.009*"organization"+ 0.009*"evacuation"+ 0.009*"protection"+ 0.008*"inform"
Improving mutual understanding between people, volunteers, and relief organizations during operations	0.033*"understanding"+ 0.013*"volunteer"+ 0.010*"better"+ 0.010*"disaster"+ 0.009*"coordination"+ 0.009*"helper"+ 0.008*"private"+ 0.008*"warning"+ 0.007*"task" + 0.007*"priority"
Avoid causing additional traffic	0.015*"instruction"+ 0.012*"understand"+ 0.011*"respect"+ 0.011*"operation"+ 0.010*"route"+ 0.010*"access"+ 0.009*"road"+ 0.008*"civilian"+ 0.008*"block"+ 0.008*"free"

Q7: Do you have any additional remarks? [coherence score: 0.45; perplexity: -7.25]

Need for timely and efficient communication	0.013*"mission"+ 0.012*"communication"+ 0.009*"staff"+ 0.008*"faster"+ 0.007*"information"+ 0.006*"lack"+ 0.006*"authority"+ 0.006*"early"+ 0.006*"warning"+ 0.006*"volunteer"
Planning, organizing, and practicing for DRR	0.010*"phase"+ 0.010*"logistic"+ 0.008*"communication"+ 0.008*"risk"+ 0.007*"training"+ 0.007*"alarm"+ 0.007*"operation"+ 0.007*"need"+ 0.007*"fire_brigade" + 0.007*"long"
Timely disaster assistance by authorities at all levels	0.012*"state"+ 0.012*"improve"+ 0.011*"organization"+ 0.009*"available"+ 0.008*"unnecessary"+ 0.008*"structure"+ 0.008*"aid"+ 0.007*"resource"+ 0.007*"accommodation" + 0.006*"federal-state"

5. Discussion

5.1. Spatiotemporal and semantic characteristics of the flood-related tweets

Human reactions, such as the frequency of communication on social media, are dynamic in response to disruptive events. A spike in the number of tweets may indicate a change in the situation or a significant impact of the disruption on people (Fan et al., 2020). In this study, the spatio-temporal observations are also consistent with the results of previous studies and official reports of the July 2021 floods. These results build on existing evidence that Twitter metadata reflect actual spatiotemporal events related to flooding and that the high density of georeferenced flood-related posts on social media is consistent with actual affected areas. The spatiotemporal pattern of social media use during disasters shows that users in affected areas tend to post more information on social media compared to unaffected users. This can provide localized and near-real-time information about evolving disaster situations for decision makers and residents (Mostafavi et al., 2017). In addition, the burst of tweets can help detect such events in near real-time, such as the detection of flooding in BY (the fifth temporal peak in Figure 5), which was underreported in the news.

In terms of semantic analysis, the pre-event topics can reflect on anticipatory and preventive capacities. For example, Figure 5 shows insufficient tweets, and Topic Modeling shows disbelief in the likelihood of flooding. This indicates that early warning systems have not used multiple/social media channels or that there is a lack of transparent risk communication. However, in terms of prevention capacity, the topic of "predicting local situations and learning from past events" shows that people who have learned from past experiences try to protect their assets and inform their peers. In the real-time phase, when people expect the disaster's effects, there is great uncertainty, and their emotional state is generally very vague (Gründer-Fahrer et al., 2018). The impact of the event often causes a shock at first and may paralyze people for a short time. After that, the heroic phase usually begins, characterized by high activity and altruism (Math et al., 2015). Most of these insights can reflect on absorptive capacity by providing evidence to improve risk monitoring and situational awareness for a better response and relief operation during such events.

After the event has passed and short-term recovery has begun, people typically experience a highly emotional honeymoon phase in which strong communal compassion and cohesion are observed, and people band together to solve problems (Gründer-Fahrer et al., 2018). There may be interruptions and relapses. Depending on the extent of the recurring threat, the new impact, or other events, it takes two to eight weeks (Math et al., 2015). After a disaster, people are often motivated to discover why an event occurred, who or what is responsible (or to blame), and how to prevent it from happening again. These discussions of socio-political and scientific causes can contribute to community strengthening and resilience (Houston et al., 2014). The data-driven topics show community discussions about socio-political and climate-related causes, collecting donations, on-the-ground assistance, information provision, and communication, as well as suggestion for adaptive and transformative measures to improve risk governance through climate policymaking and organizational innovations.

Topic Modeling of responders' answers, with their high motivation, critical attitude, and high expectations for the functioning of the administration and coordination systems, highlighted the need to improve the communication system, the timely and clear transmission of information, and better coordination and management. On the other hand, they emphasized the necessity to improve knowledge about disasters to enable better disaster preparedness and planning. This requires the involvement of all levels, local people (individuals) and stakeholders (organizations), as well as state and federal governments (institutions), to achieve mutual understanding in such situations. In the following section, the extracted topics are complied to inform disaster resilience resulting form our bottom-up processing.

5.2. Compilation of extracted topics from Twitter and online survey in the context of resilience capacities

In this section, in-depth analysis of the two data sources led us to compile extracted topics under the five overarching resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative) (Manyena et al., 2019) to reflect people's collective insights, experiences, and opinions related to flood disaster for improved disaster resilience in general. This sensing approach provides localized knowledge and information for disaster resilience initiatives to develop practical solutions, that reflect the community's place-based needs and capacities.

Figure 8 thus reflects the collective opinion on flood-related issues and capacities categorized under the above mentioned resilience capacities.

The findings underscore the need for multi-level and cross-sectoral planning and education to reduce disaster risk. Sustainable and risk-sensitive land use planning, such as the location of wind farms and the ratio of the sealed area upstream of the flood-prone zone, is emphasized. Critical infrastructure robustness was under criticism due to massive damage to water, power, and transportation systems. Based on the results, the redundancy of communication networks and communication channels should be considered to tackle problems imposed by power outages and interruptions in Internet connectivity. Response capabilities in uncertain and time-critical situations should be improved through disaster-related training and coordinated mobilization of resources. On the other hand, community-level preparedness is emphasized, such as the importance of insurance against flood hazards, which shows the community's willingness and knowledge to take action.

Collective knowledge to improve anticipatory capacity emphasized the need for foresight and timely recognition of threats, consideration of uncertainties, the establishment of effective early warning systems using multi-level and multichannel communication, training decision makers and communities on uncertainties, and improving their disaster-related knowledge and skills. In addition, the problem of disbelief in the likelihood of flooding and lack of preparedness for unforeseen events indicates that further study is urgently needed on how such risks should be assessed and communicated at all decision-making levels to avoid such disasters in the future.

To improve absorptive capacity and reduce the number of affected people and assets, the collective insights point to the need for practical collaboration among organizations, volunteers, and affected populations based on an established mutual understanding; and better coordination and management of resources and human capital in disaster response. Moreover, the findings show the criticism of site selection for critical services such as health centers, which should not be located in flood-prone areas. However, the results show that social cohesion and community solidarity, as well as high levels of humanitarian assistance and crowdfunding, which are important indicators of socioeconomic resilience, were positively evaluated by people.

In improving adaptive capacity, people addressed the need for socio-egological adaptations to climate change impacts, such as soil erosion control, environmental and cultural heritage protection, and better ecosystem monitoring. They emphasized the need for government investment in socioeconomic security, capacity building, and empowerment of local authorities (municipalities) and communities to have active decision-making roles in emergencies. They also emphasized the need for education and training in response and recovery skills for all groups and practical tools for better risk communication in a transparent, clear, and continuous format. The emphasis on flood insurance penetration indicates that people are socioculturally aware of the insurance gap, and therefore strategies should be developed to insure more people exposed to flood risk.

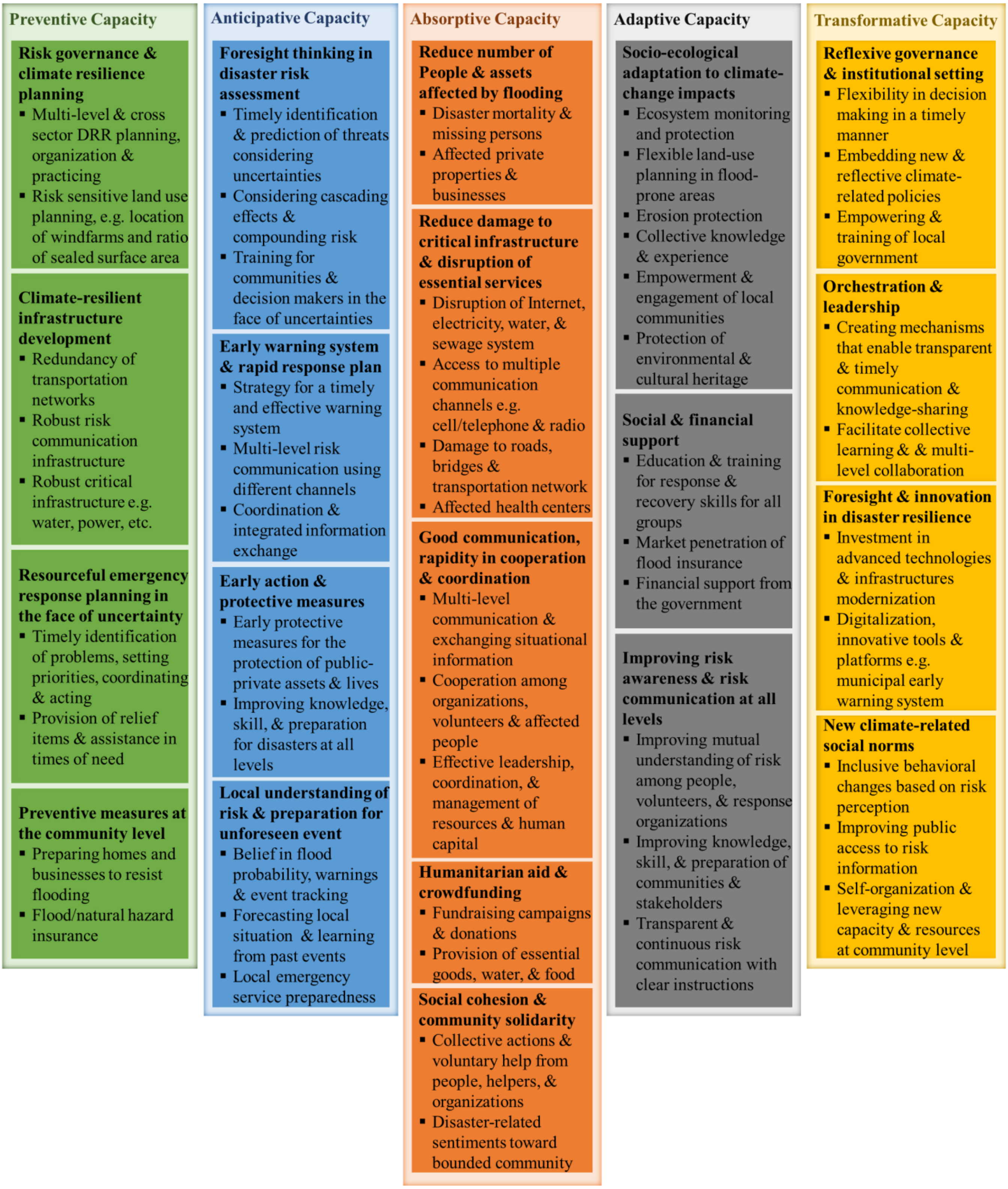


Figure 8: Compiling social media and online survey topics under resilience capacities themes toward resilient community development in Germany

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For transformational resilience, the public reaction and sentiment toward the government's approaches reflect the need to incorporate new climate-related policies, investments in advanced technologies and infrastructure modernization, and new platforms and innovative municipal early warning systems to improve resilience. In addition, it has been highlighted that local governments should be equipped with an effective coordination mechanism in disaster management that allows for multi-level collaboration and flexible decision-making processes in time-critical situations. The wisdom of the crowds also reflects the importance of new social norms and values that lead to long-term behavioral changes to reduce the impacts of climate change, indicating the contributors' exemplary climate-related knowledge. Finally, the result shows that individuals and communities supported self-organized peer-to-peer relief efforts using their capacities and resources. Better information flow, therefore, results in increased self-organization among the population affected by disasters.

This in-depth contextual analysis, along with the temporal and spatial proximity of social media posts and the online survey, allows disaster management agencies to hear from the public and build resilience capacity based on the collective sociocultural characteristics of the community. Moreover, this bottom-up and web-based approach could be a near real-time alternative or complement traditional participatory methods and techniques of organizing interviews, meetings, and workshops for situational analysis and unfolding of such events that usually last months.

5.3. Key challenges and future research

Any research approach faces challenges and is subject to certain limitations that are difficult to overcome. It is well known that social media and online surveys are not representative of the entire population. Issues such as unequal access to web-based tools (e.g., technology, skills, education), digital disengagement, and trust and privacy concerns could pose challenges in such studies. However, the rapid advances in technology, society, and digital innovation as influential drivers can provide opportunities to develop shared and collaborative platforms that all can use with different levels of education, knowledge, and skills.

Moreover, while LDA is one of the best and most widely used algorithms for topic modeling, processing its results can be challenging. Labeling the results requires a high level of expertise and is labor-intensive and time-consuming. This should be addressed in future work to facilitate practitioners and researchers in the timely use of such large datasets in decision-making processes.

Based on our research goal to obtain collective knowledge, the spatiotemporal analysis of tweets was limited to the country level due to the dramatic flooding across the country. However, according to the German constitution, which grants the states the authority to enact emergency management laws, there are differences among the states regarding leadership, training, and types of equipment. Therefore, future studies could analyze the tweets with state boundaries and compare the results with this study.

Monitoring and assessing climate resilience at multiple temporal and spatial scales is key to developing proactive management strategies to address climate change. One of the major challenges in measuring disaster resilience is the inclusion of soft sociocultural factors. This study demonstrates the potential of crowdsourcing data as a rich data source for these attributes such as community solidarity, learning from the past, social cohesion, and experience. Thus, further studies are needed to enable the integration of these into the measurement and monitoring of resilience dynamics.

6. Conclusion

As extreme events induced by climate change will continue to increase in frequency and severity, we should harness the power of today's web-based communication culture to enable the timely sharing of disaster-related information, situational awareness, and unfolding of unforeseen situations. Since the July 2021 flood disaster in Germany became a tipping point for questioning community vulnerability and risk governance and practices in the face of an unexpected event, this study, analyzed two data sources, Twitter data (passive crowdsourced data) and an online survey of responders involved in the relief effort, to explore the wisdom of the crowds on that. To this end, we used the LDA method for Topic Modeling for text analysis and coded collective insights at near-real-time of flooding. In addition to semantic analysis, spatiotemporal patterns of online disaster communication were analyzed to determine the contribution patterns associated with the affected areas.

The findings provide an evidence-based and bottom-up approach to disaster resilience by optimizing the diversity and spectrum of experience and knowledge of contributors with different backgrounds on flood resilience and reflecting their sociocultural characteristics. Based on the findings of this study, to improve flood resilience, preventive and anticipatory resilience strategies such as adopting sustainable pathways (e.g., risk-sensitive land use planning and climate-resilient housing and infrastructure) and effective risk governance considering uncertainties (e.g. clear risk communication and multi-level early warning system) should be strengthened. This requires co-design and multi-level collaboration with a shared resilience vision. In addition, adaptation to the changing environment (e.g., empowering local governments and communities and market penetration of flood insurance) and achieving transformation (embedding new climate-related policies and social norms) should be promoted based on new norms, values, and flexible structures in risk thinking and governance. This needs improved risk knowledge at multiple levels, collaborative learning processes, and leveraging innovative tools and new data sources that lead to improved disaster resilience.

Passive crowdsourcing combined with online surveys as a bottom-up approach provides a more timely and cost-effective alternative to other participatory techniques, such as organizing meetings and workshops to analyze situations and unfold such events, and enables the participation of citizens who are not otherwise involved in scientific or administrative activities. This approach can also help capture soft sociocultural factors such as the extent of community solidarity or community readiness for climate-related policies. Considering collective insights, perceptions, and expectations as part of the decision-making process helps identify short-term priorities for action and ultimately develop place-based disaster resilience strategies based on the community's medium- to long-term needs and capacities. Finally, as part of such bottom-up processes, we should be mindful of issues such as the digital divide, local disparities, and digital disengagement.

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CHAPTER 6

RESEARCH IMPLICATIONS AND LIMITATIONS

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1. Research implications

In times of climate change, progress toward resilient and sustainable development can benefit from challenging assumptions and patterns and encouraging innovation to inspire new paradigms. Learning processes, both top-down and bottom-up, are crucial to building resilience capacities and outcomes in disaster risk management, climate change adaptation, and sustainable development, particularly in the face of extreme and unforeseen events. Achieving resilience requires leveraging new data and approaches, especially when combined with capacity building rooted in the local context. Therefore, as described in Chapter 1, this study aimed to improve and propose new ways to operationalize the multifaceted concept of community flood resilience by applying new nomothetic/top-down and idiographic/bottom-up methodological approaches and developing a framework that can serve as a guiding mechanism for using geographic crowdsourcing knowledge to scale transformation and innovation in approaches to disaster resilience. To this end, three main objectives have been formulated. This Chapter reviews and discusses these objectives and their associated outcomes and implications.

Objective one: Quantification and benchmarking of the resilience baseline conditions by performing an index-based resilience measurement to be able to understand the pattern of urban flood resilience, underlying the contributing factors, and prioritizing interventions (Case study for this Nomothetic/top-down approach: Iran, Tehran's 22 urban districts)

A review of the existing literature has shown that the first milestone in understanding the factors and interactions that contribute to disaster resilience is to measure the baseline state of resilience. However, several gaps were identified in the literature, such as the lack of agreement on the approach to measuring disaster resilience at the community level and a standard process for developing composite indicators. This suggests the need for more empirical research to assess urban resilience and a flexible and transparent process for developing resilience indices. Therefore, these gaps are addressed in the first contribution in Chapter 3.

From a theoretical perspective, although the first contribution adopted the BRIC framework to develop a deductive approach for operationalizing the concept of flood resilience, it questioned the equal weighting approach for building composite indicators. The study argued that the importance of certain criteria may differ in different contexts and scales and emphasized that equal weighting cannot capture the interconnectedness of indicators in such a multidimensional phenomenon. In contrast, the study proposed the use of unequal weighting methods to integrate the knowledge of experts from different disciplines and make an empirical assessment based on local characteristics and capacities.

From a research perspective, the study provided a clear and transparent step-by-step approach to benchmarking disaster resilience as guidance for such studies, including the selection of a conceptual framework and identification of sound and valid indicators, multivariate analysis, and data reduction using hybrid MCDM methods to weight indicators and comparatively assess community resilience levels, mapping of the disaster resilience index, and validation of results.

From a practical point of view, the first contribution was one of the first attempts to develop an index-based measurement using a hybrid AHP-TOPSIS method for comparative flood resilience assessment for Tehran, the capital of Iran. This can inform decision-makers to prioritize and outline areas that need more interventions regarding risk-informed planning and management.

Objective two: Understanding the capacities of VGI and crowdsourcing geographic knowledge for resilience enhancement and developing a framework as a guiding mechanism to utilize VGI toward scaling transformation in disaster resilience initiatives

After benchmarking resilience baseline conditions, new ways to improve community resilience using other data sources arising from sociotechnical advances such as crowdsourcing geographic knowledge was explored. However, a literature review on VGI and transformative resilience revealed a lack of comprehensive understanding of the complexities and capacities of using such data for transformative resilience. Therefore, the second objective (the second contribution presented in Chapter 4) first addressed the concept of transformative resilience to emphasize the need for innovative and collaborative learning and inclusive co-creation of knowledge. It then explored the key aspects of using VGI for transformative resilience and proposed a comprehensive framework that encompasses the identified legal, institutional, social, economic, and technical aspects to formalize the process of using VGI and crowdsourcing information in transformative resilience initiatives.

From a theoretical perspective, the framework developed provided a comprehensive and multidimensional view to enhance understanding of how crowdsourcing can be used for disaster resilience, particularly for transformative approaches that aim for reflexive governance with empowered people and the use of technology-enabled approaches as facilitators. The study also highlighted considerations that should be made through comprehensive research on various aspects of crowdsourcing and could serve as an agenda for future research.

From a research perspective, this study fills a research gap by providing an overall picture of VGI in relation to disaster resilience that takes into account a comprehensive understanding of the complexities and interrelationships among legal, institutional, technical, economic, and social aspects within each jurisdiction.

From a practical perspective, the framework in this study could be viewed as a flexible roadmap, that can be modified depending on emerging insights, for researchers and practitioners on how and with what considerations Big Data and citizen-generated data can be used in disaster resilience initiatives.

Objective three: Near real-time analysis of crowdsourcing social media (semantic and spatio-temporal analysis) and online survey for data-driven disaster resilience enhancement and informing disaster resilience capacities (idiographic/bottom-up approach; Case study: the July 2021 flood disaster in Germany)

After benchmarking baseline conditions for resilience using a top-down approach and developing a framework for leveraging sociotechnical advances such as crowdsourcing of geographic knowledge for transformative and bottom-up approaches in disaster resilience studies, the third objective was established. The third contribution, presented in Chapter 5, therefore conducted data-driven and idiographic research using social media crowdsourcing and an online survey. This contribution aimed to capture the dynamics within large communities of individuals and situational (spatiotemporal) analysis in the case of the devastating floods in Germany in 2021. In addition, social media messages and survey responses were coded and compiled using Topic Modeling through ML as perceptions and expectations of people and stakeholders for improved disaster resilience within five resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative).

From a theoretical standpoint, the study argued that data-driven and bottom-up approaches complement indicator-based resilience measurement and that disaster resilience as a dynamic process can benefit from techno-social advances to capture dynamic patterns within communities through large-scale observations and social sensing techniques. It was also proposed to contribute to the urgent need to shift from a reactive to a proactive approach to disaster resilience by developing mechanisms based on open and near real-time access to spatial and risk-related information, enabling better and faster communication, knowledge sharing, and collaboration in decision-making processes across scales, actors, and people, and fostering synergies and minimizing conflicts in order to improve the overall resilience of communities.

From a research perspective, the third contribution was one of the first attempts to code and then analyze both flood-related social media messages (attitudes of the public) in near real-time and the responses of stakeholders involved in disaster mitigation (opinions of stakeholders) on disaster-related topics and compile them into five disaster resilience capacities. This data-driven evaluation can contribute to the timely and evidence-based development of community-based disaster resilience strategies to not only strengthen the collective resilience of communities to unforeseen disasters but also to consider transformative ways to prevent such climate-related disasters in the medium to long term.

From a practical perspective, the study provided a clear approach to identifying and encoding collective insights (wisdom of crowds) in near real-time and to understanding semantic and spatiotemporal dynamics within large communities of individuals for data-driven situational analysis. This approach (crowdsourcing and online survey) can enable researchers and practitioners to access a large amount of local knowledge before, during, and shortly after unforeseen events to quickly and effectively mobilize expedient resources and make evidence-based decisions.

2. Key challenges and limitations

Every research faces certain challenges and is limited to some degree by constraints that are difficult to overcome. The main limitations and challenges in this research are listed in the following based on the three main objectives and the corresponding contribution.

Objective one: A common limitation in composite indicator building to operationalize the concept of community disaster resilience is the availability and accessibility of data for each of the indicators identified. Consequently, some of the variables should be excluded due to unavailability or inaccessibility, which could affect the results of the study. For example, in the first contribution, institutional resilience, which plays an important role in all disaster management phases, is quantified by only two variables due to this limitation.

Regarding the proposed MCDM method, it should be noted that the AHP pairwise comparison can only consider a limited number of variables because it is cognitively demanding. Moreover, validation of disaster resilience studies is often problematic due to a lack of information on the impact of past natural disasters and therefore, validation based on actual flooding events in Tehran was not possible.

In summary, while this nomothetic (top-down) assessment is amenable due to the use of standardized data, such measurements may not adequately account for dynamics within communities, ongoing or emerging capacities, and needs, and therefore, bottom-up approaches are also necessary to complement the understanding of disaster resilience.

Objective two: In the second contribution, the proposed framework was structured around legal, institutional, social, economic, and technical aspects to formalize the process of using VGI and crowdsourcing information in transformative resilience initiatives. Accordingly, the concerns and challenges associated with the use of such data sources have also been presented through these five thematic aspects.

Since legislation typically lags behind technical developments, the use of crowdsourced geographic information in official databases may be restricted in certain jurisdictions. Thus, the design and implementation of new legal frameworks, policies, and open standards for open-source and user-generated geospatial content must be considered at all governance levels. In addition, from an institutional perspective, a VGI paradigm would suggest a new interaction between governments and citizens, which might be difficult for national institutional structures that are not linked to local and community activities. As a result, the amount of interest and active engagement of government agencies, as well as regulatory enforcement, may impact the development and outcome of VGI-based initiatives, as well as slow down VGI project originality and innovation.

From a technical standpoint, the emergence of VGI as Big Data has increased the volume, velocity, and variety of geospatial data generated, and the linkage to geospatial applications has led to a fundamental shift in how this data is managed, stored, processed, and used. This underscores the need for new tools and methods to manage, curate, and analyze data. In addition, the reliability and validity of VGI data and metadata, as well as their intrinsic and extrinsic quality, should be explored as part of the initiative. To overcome these limitations, it is necessary to design a data protocol between the stakeholders and systems involved based on the project goals.

From a socio-economic viewpoint, VGI-based initiatives should also consider issues such as local differences, the digital divide, marginalization of certain groups, community acceptance of the technology, openness to digitization, reliance on digital data collection devices, privacy concerns, and ethical issues in collecting and publishing VGI in practice.

Objective three: The third paper developed an idiographic/bottom-up approach to data-driven disaster resilience improvement and informing disaster resilience capacities using social media crowdsourcing (Twitter platform) and an online survey. When mining tweets in this study, the detection of tweets depended on a set of predefined hashtags because most methods for automatically detecting tweets focus on English-language data. Another limitation was the lack of geographically localized tweets. Although Twitter offers several options for determining geolocation, the most accurate of these is the option for users to send their coordinates along with the tweet, which comprises about 1% of tweets. Finally, it should be noted that labeling the results as the output of the LDA model required a high level of expertise and was labor-intensive and time-consuming.

CHAPTER 7

CONCLUSION AND DIRECTION FOR FUTURE RESEARCH

CHAPTER 7: CONCLUSION AND DIRECTION FOR FUTURE RESEARCH

1. Conclusion

Given the critical importance of community resilience in times of climate change, this study sought to propose new ways to operationalize the multi-faceted concept of community resilience to flooding through a nomothetic/top-down approach and present a framework and idiographic/bottom-up method, that leverages crowdsourced knowledge toward data-driven collective resilience to flooding, highlighting the role of socio-technical evolution in scaling transformation and innovation in disaster resilience approaches. This chapter concludes the study by highlighting key findings based on the research objectives and making recommendations for future research.

From an idiographic or top-down perspective (the first research objective presented in Chapter 1), in order to operationalize the concept of disaster resilience in the context of an empirical study, the first contribution represented a multi-criteria approach to assess flood resilience in Tehran, Iran. In Chapter 3, the study proposed a simulation model that assessed inherent flood resilience (or baseline resilience) in the urban districts of Tehran by conducting an index-based approach that considered quantifiable variables (33 individual indicators) obtained through a stepwise composite indicator-building approach (first objective, research question 1). Then, a hybrid multi-criteria decision-making method was developed using a combination of the AHP for prioritizing and weighting the identified indicators and the TOPSIS for comparatively ranking Tehran districts based on their resilience levels (first objective, research question 2). This hybrid approach provided a tool for integrating the qualitative assessment with the quantitative analysis and demonstrated that in developing a place-based disaster resilience assessment, each indicator would have a different impact on the resilience level depending on its importance. This statistical approach summarized the measurements by aggregating multiple indicators into six dimensions of social, economic, institutional, infrastructural, community capital, and environmental resilience, as well as an overall index of the District's resilience to flooding. The index represented the multidimensional nature of community resilience, including underlying factors. The results also indicated that the use of standardized data (secondary data) makes these types of resilience indices more appropriate for examining spatial variability (administrative boundaries), resource allocation, and/or community-level monitoring. However, the results also highlighted that such top-down approaches cannot adequately address resilience capacities and dynamics in communities. Therefore, complementary bottom-up approaches are also needed to achieve a more participatory and dialogic model using new and innovative methods for disaster resilience (first objective, research question 3).

To open up opportunities for linking top-down and bottom-up approaches to enable transformation in disaster resilience, the role of digital technologies and data innovations, such as Big Data and citizen-generated data, should be explored. Therefore, to address the second research objective, Chapter 4 explored the capacities of crowdsourcing geographic knowledge and VGI with regard to transformative resilience pathways aimed at reflexive governance with empowered people and technology-enabled approaches. Based on the concept matrix method, 18 key VGI aspects (or capacities) for disaster resilience were identified and then coded into five thematic domains, namely social, economic, technical, institutional, and legal (second objective, research question 1). Each aspect within the corresponding domain was presented in varying degrees of comprehensiveness with respect to the resilience characteristics that lead to scaling transformation. Indeed, the overarching capacities of this data in terms of how it is generated, shared, and used were related to enabling inclusive knowledge co-creation, collaborative and collective learning, empowering self-organization processes, and mobilizing cutting-edge technologies and new services in the face of unforeseen disasters (second objective, research question 2). Finally, a comprehensive framework structured around these aspects was proposed to formalize the process of leveraging crowdsourced information and VGI in transformative resilience initiatives (second objective, research question 3). This framework was developed to provide an overall perspective on the functions, capacities, and challenges of VGI and crowdsourcing to consider when integrating them into transformative resilience processes. The findings also concluded that VGI-based models can be considered as either stand-alone or complementary mechanisms when conventional approaches are less suitable for promoting collective community resilience by capturing dynamics within communities, or when administrative datasets are less suitable for providing open, accessible, and timely geospatial data to both the community and decision-makers.

From a nomothetic or bottom-up perspective (the third research objective), and building upon the proposed framework, Chapter 5 contributed to complementing our understanding of resilience capacities by capturing dynamics in large communities of individuals and the spatial extent of the 2021 flood situation in Germany within a timely situational analysis using social media crowdsourcing and an online survey. Through semantic analysis of two data sets by LDA an unsupervised ML model, the study reflected people's and stakeholders' perceptions and expectations (the wisdom of crowds) for improved disaster resilience within disaster phases and compiled the extracted topics into five disaster resilience capacities (preventive, anticipative, absorptive, adaptive, and transformative). The findings related to the analysis of the spatio-temporal behavior of disaster-related georeferenced tweet activity at the Federal State level in different disaster phases revealed that Twitter metadata indeed reflected real geospatial events related to flooding and that the high density of georeferenced flood-related social media posts was highly consistent with actual affected areas since users in affected areas tended to post more information on social media compared to unaffected users. In addition, the burst of flood-related tweeting during floods could contribute to the timely detection of such events and the needs of communities to mobilize expedient resources and make informed decisions (third objective, research question 1). The findings of the proposed real-time collective sensing approach provided insights on how leveraging crowdsourcing knowledge enables innovation embedding for faster sharing of various disaster-related geographic information at a fraction of the cost associated with traditional data collection and dissemination, as well as real-time dynamic monitoring, multidirectional communication, and better situational awareness in unforeseen situations. The findings on compiling the extracted topics also highlighted that preventive and anticipatory resilience strategies, adoption of sustainable pathways, systemic risk assessment, and governance considering uncertainty should be strengthened through co-design and multi-level collaboration with a shared resilience vision in Germany. Adapting to changing environments and achieving transformation based on new norms, values, and structures in risk thinking and governance and improved local risk knowledge and behavior change should be also encouraged. (third objective, research question 2).

With minding the digital divide, the power of today's communication culture (mobile communication and wisdom of the social media crowds), where prosumers provide their location-based knowledge and services, as well as the advanced computational sciences and technologies (machine learning, artificial intelligence, crowdsourcing, Digital Twins, etc.) for Big Data analysis and real-time measurement should be harnessed to enhance collective climate resilience of all communities and prevent climate-related disasters.

2. Future research

Based on the investigations conducted in this research, it is recommended that future research efforts could be directed to the following areas:

- The procedure of composite indicator building for the flood resilience index has the potential to be improved if the data for some of the variables are accessible or available. Moreover, different MCDM approaches can be proposed and compared with the AHP-TOPSIS model. Since MCDM methods help to capture experts' opinions and involve stockholders with different backgrounds, a sensitivity analysis could be conducted as well to increase the credibility of the decisions.

- To better understand the implications of the presented framework, future studies could address additional testing and refinement of the framework in various concepts and contexts to achieve a more mature framework. Future research could also investigate how specific projects across jurisdictions are able to integrate crowdsourcing and VGI data for resilience initiatives and examine corresponding opportunities and challenges.
- To overcome the methodological limitations of this study, future research could use more data sources, such as Facebook or Instagram since additional platforms might provide additional inputs on resilience aspects not yet captured. Any new results then need to be integrated into reseilience strategies.
- Rapid advances in technology, society, and digital innovation are influential drivers that may influence the direction of future research and provide opportunities to refine and expand the approaches for disaster resilience. Therefore, foresight analysis related to advances and changes in these domains can contribute to understanding new approaches for tackling climate-related risks and the development of strategies for resilience.

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