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Comparing networked and linear risk assessments: From theory to evidence

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ABSTRACT

Disaster risk has long been conceptualized as a complex and non-linear set of interactions. Instead of evaluating risks as isolated entities, 'networked' risk assessment methods are being developed to capture interactions between hazards and vulnerabilities. In this article, we address three challenges to networked risk assessments: the limited attention paid to the role of vulnerability in shaping risk networks, the unclear value of networked assessments compared to linear ones, and the potential conflict in linear and networked assessments at theoretical level. We do so by providing one of the first comparisons between linear and networked assessments in an empirical case, the risks faced by businesses operating in Iran's Razavi Khorasan Province. We find that risk rankings vary depending on whether risks are assessed using linear or networked techniques, and that vulnerabilities feature prominently in networked risk results. We argue that although networked and linear techniques rest on fundamentally different ontological conceptualizations of the world, approaches are complementary and reflect different dimensions of risk, and can be used in conjunction to provide a more comprehensive view of risk.

1. Introduction

Disaster risk has been conceptualized as a network since at least the 1970s, when Wisner et al. [60] described the "vicious circles" between disaster, vulnerability, and hazards in their article on the societal dimensions of risk. Technological, social, economic, and political interconnections have only increased [26], and networked approaches to risk have gained considerable attention across the field of disaster studies in the years since. The hazard paradigm has focused on how interactions between technological systems create risk, the vulnerability paradigm on the co-constitutive nature of hazards and vulnerability, and the resilience paradigm on how risk emerges as the outcome of an open-ended and evolving system [16]. The work on disaster cascades, understood as the highly complex and nonlinear causal sequences of events that shapes disaster [45], exemplifies this networked perspective. Cascade research has shown that to fully understand risk, serious attention must be paid to the ways in which systems and system components interact to shape hazards and vulnerabilities. Since risk emerges out of system interactions, interventions that treat risks as distinct from each other and fail to account for interconnections can reinforce the underlying processes creating risk [44,58].

Several approaches have been developed to assess the networked dimensions of risk. All stem from a perspective that measuring risk as a combination of a hazard's probability and impact in isolation to other hazards and vulnerabilities — what we term linear risk assessments — miss interactions that fundamentally shape risk. A large body of literature has developed assessing critical infrastructures from a networked perspective, including their interdependencies, cascade potential, and resilience [43,46,34,21,31,32] ([19]). Other work has focused on interactions between risks, such as between natural hazards, anthropogenic processes, and technological hazards [23–25], between global risks [61], or risks at local level [11,40,42].

While progress has been made in networked risk assessments, we have identified three challenges still to be addressed. First, the emergent nature of vulnerability is rarely included in networked risk assessments. Instead, assessments tend to focus on interactions between hazards or between technological systems and do not show how vulnerabilities are affected in disaster cascade sequences. Since vulnerability is an essential part of risk, it difficult to fully understand how disasters cascade without including interactions between both hazards and vulnerabilities [45]. Second, to the best of our knowledge, results of networked and linear assessments have not yet been compared. Without these comparisons it is not clear how networked and linear risk assessments equate or even whether adapting a networked approach changes risk scores. This makes it challenging to determine the value of networked risk assessments vis-a-vis linear assessments. Third, the

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theoretical foundations of networked and linear assessments are not explicit, and may be grounded in different conceptualizations of the world. Referencing the “non-linear”, “emergent”, and “complex” nature of risk [2,45,8], networked assessments seem to operate from a post-modern relational ontology, while linear assessments contain simple assumptions of causality that seem rooted in a modernist worldview emanating from the Enlightenment. Such differences might create irreconcilable differences between assessment techniques.

The purpose of this article is to clarify the relationship between networked risk assessments and their linear counterparts. To do so we provide one of the first comparisons between the theory and practice of these two assessment techniques. We first review existing knowledge to establish the theoretical foundations of linear and networked understandings of risk. We argue that despite their different ontological foundations, a pragmatist orientation found within disaster studies can be adapted to employ linear and networked assessments to be concurrently. Second, using key informant interviews, surveys, and focus groups, we undertake a networked and a linear risk assessment of the risks faced by businesses operating in Khorasan Razavi Province, Northeastern Iran. To capture the importance of vulnerability in shaping risk we employ a broad conceptualization of what constitutes a risk that includes hazards, hazard drivers, and vulnerabilities. When we compare results, we find that linear and networked risk assessment results differ in how various risks are ranked, and that these rankings capture different dimensions of risk. We conclude by discussing the implications of this study and outlining future research.

2. Linear and networked theories of risk assessment

Linear and networked risk assessment approaches conceptualize the world and their risks in different ways. From a linear perspective, risks are an additive product of their constituent parts. This perspective becomes clear when examining how the term ‘risk’ is used in the context of disasters. Risk has many meanings [3] but from a linear viewpoint, it can be defined as a combination of the probability of a hazard with its impact. This relationship is frequently formalized in the equation: *risk = probability x impact.* Natural and human-made forces determine a risk's probability and impact. Hazards, “a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation” [55] can be natural, human derived, or some combination of the two. While hazards are not always human derived, vulnerabilities, “the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards” [55], always have human dimensions.

Networked approaches to risk conceptualize people, environments, technologies, economies, and institutional systems as inseparably interconnected as part of an ever-evolving open-ended system. These interconnections afford both economic and societal efficiencies but can also create potentials for hazard and vulnerability cascades [27,46]. Instead of being a combination of the direct probability and impact of a hazard, probability and impact are relational, with risk derived from its connections with other hazards and vulnerabilities. Risk is thus a measurement of a hazard's ability to reverberate and cascade across a system and affect other vulnerabilities and hazards. The organizational sociologist Charles Perrow lays the groundwork for this type of approach in his classic work on what he terms a ‘normal’ or ‘systems’ accidents, the accidents that emerge as systems become more complex and tightly coupled [44]. Perrow proposes that, while most disasters are a result of a lack of political will or motivation to reduce risk, certain system structures are inherently risky. While Perrow reviews the technological dimensions of system coupling and complexity, Diane Vaughan [56] extends normal accident theory to the social dimensions of systems to show that the complexity and coupling of regulatory and cultural processes can also lead to system accidents. Vaughan's perspective aligns with arguments that vulnerabilities, created by social systems and power relations operating across multiple levels and timescales, play a major role in shaping risk and disaster [59]. In this view, it is the accumulation and alignment of vulnerabilities that creates the potential for risk cascades [45].

The networked structure of risk creates non-linearities. The temporal dimensions of networked risk, or a risk's reverberation over a period of time, mean that probability and impact evolve continuously from endogenous network interactions and can lead to radical system transformations that are completely self-driven. Interdependencies between system components mean that vulnerabilities and hazards can double back, amplify, and magnify each other [1,49,59]. The work on traps shows how interdependencies can result in vicious feedback loops: violence can beget more violence, poverty more poverty, and disasters more vulnerabilities, hazards, and disasters [13,7,9]. Nonlinear interactions can also create fundamental changes in systems, resulting in new systems with wholly different relational configurations and functions [30,36,8]. This property, known as emergence, means that system dynamics can change in ways that are impossible to fully predict.

Non-linearity leads to a fundamentally different view of the world than linearity. The direct causality and closed system underlying linear views of risk reflects a rational clockwork view of the universe that has its roots in the modernist worldview of the Enlightenment [4]. In this worldview, since events are the direct result of a discrete set of causes and effects, the universe and its risks are ultimately completely knowable. A related perspective holds that processes are linear but it is not yet possible to fully understand the factors shaping risk with current scientific techniques. According to Chandler [10], this view also stems from same underlying Enlightenment ontology of the world and frames understanding risk as an epistemological challenge. In contrast, emergence means that understanding risk is a problem of ontology, not epistemology. The nonlinear and open world of emergence means that there will always be unexpected outcomes arising from random interactions between system components and that surprise is inevitable regardless of advancements in risk assessments.

These different views of risk emphasize different elements of risk management. Simple and linear views are expressed in the hazard paradigm, which holds that experts using the latest scientific techniques are best positioned to assess risks through a centralized command and control structures [28], or, with incomplete knowledge, through neoliberal forms of risk governance where experts centrally assess systems and set the broad rules to guide local stakeholders [10]. In contrast, an emergent world crisis is unavoidable, so instead of attempting assess and control risk, efforts should focus on reacting to emergence through continuous learning and self-reflexive transformation. Many of these properties are expressed in the idea of resilience, a disputed concept rooted in several disciplinary traditions, but generally understood as the ability of a system to withstand, recovery, and in some cases transform in response to disruptive events [33,39]. Resilience operates from a perspective of relational complexity wherein disasters are inevitable due to unexpected interactions between systems. As such, rather than trying to prevent disasters from occurring, efforts should be made to reduce their impact through interventions that improve preparedness and response capacity and promote adaptation [57]. However, since many disasters do not arise unexpectedly but are rather predictable outcomes of social processes, prevention and mitigation should feature heavily as a part of managing risk [44,59]. Furthermore, resilience is itself an emergent property that can arise and collapse as an outcome of interactions between system processes, meaning that efforts to build resilience may be unsuccessful and fail [2].

3. Linear and networked multi-hazard risk assessments

In this section, we examine the implications of these different understandings of risk for conducting multi-hazard risk assessments. Acknowledging that the term “multi-hazard” differs depending on the contexts [24], we understand multi-hazard risk assessments as the process of identifying, categorizing by a normalized probability and impact, and comparing risks found within the same context or circumstance. We focus on multi-hazard risk assessments due to their ubiquity within the field of disaster management. Such assessments are used across all levels and sectors of society. International organizations such as the United Nations and the World Bank advocate for and employ multi-hazard assessments, as do national disaster management agencies such as the Federal Emergency Management Agency of the United States. Corporations also frequently conduct multi-hazard assessments, often as part of a whole of organization enterprise risk management program. Along with their widespread use, these assessments also typify linear conceptualizations of risk. Characterizing risks as an outcome of probability and impact offers a mechanism for ranking risks with a numeric score that can be used as a rational foundation for prioritizing interventions [20,41]. For instance, risks with high probability and impact can be considered critical risks and should be intervention priorities, while risks with lower probability and impacts are less significant and can be addressed as resources allow. In other words, instead of accounting for interactions between risks, hazards, and vulnerabilities, risks are treated as distinct entities that do not interact to shape probabilities and impacts.

There have been efforts to incorporate networked perspectives into multi-hazard risk assessments and to develop networked risk analysis techniques that can be employed for multi-hazard assessment. However, ontological foundations of networked risks create questions about the validity of such assessments. In open systems, both experts and the risk assessments that they produce are inseparable from the risk contexts: assessments are based on categories with shaky, socially constructed foundations [17,62] and are conducted by stakeholders whose expertise both shapes and is shaped by the risk landscapes that they seek to assess [52]. Because risk assessments cannot be separated from their context, assessments reflect cultural and institutional norms, not an underlying risk reality. Furthermore, emergence means that reconfigurations of technologies and modes of organizations can lead to unknowable and novel accident configurations [18]. Schulman and Roe [47], for instance, reveal emergence within disaster management when they describe how infrastructural interdependencies change depending on whether infrastructures are operating normally, or in disaster, response, or recovery phases, with different stakeholders playing different roles in different points in time and those roles evolving in response to stakeholder decisions. There are also challenges in delimiting boundaries of risk systems. Boundaries of open systems are by nature artificial, and often lie latent to only become fully visible following disaster [37,44]. In total, these properties mean that ‘unknown unknowns’ are inseparable parts of risk networks and that rather than being objective representations of a risk, risk assessments are “fantasy documents” [12] that function as reassuring symbols of control and knowledge and mechanisms for control and knowledge.

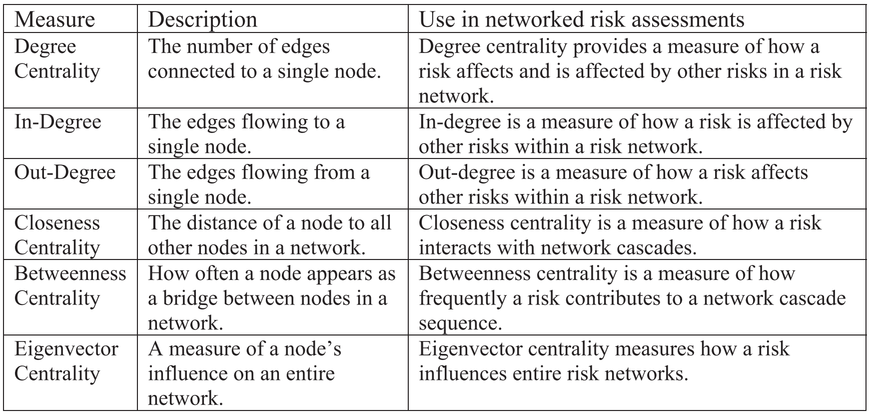
While a complex relational ontology of the world raises important questions about the certainty of risk assessments, networked risk assessments can still be conducted by following the well-established pragmatic approaches of disaster studies. Disaster studies has a practical orientation focused on improving the way risks are managed in society [29,54]. Although this perspective may marginalize more constructivist social theories [54] it provides a mechanism for using whatever risk assessments provide the best approximation to people's lived disaster experiences [59]. Even though ontology contradicts epistemology, networked risk assessments can be conducted if they are approached from a knowable practical grounding focused on improving practice. Networked and linear approaches can be incorporated together in an uneasy alliance as long as results improve the utility of risk assessments.

3.1. Network analysis as a tool for networked risk assessment

Network analysis can be used to perform multi-hazard risk assessments. Network analysis is a method for assessing systems, which are comprised of points that perform a specific function called nodes, and connectors linking those nodes together known as edges [35,50]. From a network analysis standpoint, hazards, vulnerabilities, and hazard drivers can be conceptualized as nodes, the interactions between them edges, and the overall risk network a composite of those nodes and edges. Network analysis approaches systems from a position of relational complexity, where the edges connecting nodes determines the attributes of the nodes, and the structure of edges determines the performance of the overall system [35]. Network analysis can reveal complex patterns of data including how dependencies and interdependencies shape overall risks, so fits with the network dimensions of risks. Results of network analysis can be summarized using visualizations, which can help to quickly understand structures of risk interactions. In network analysis edges can be directed, indicating that the relation between nodes has a causal direction, or undirected, showing that nodes are connected but not providing information on the direction of connections. Since risks interact sequentially, edges of risk networks should be directed.

Network analysis provides several measurements that are useful for assessing risk networks. Clark-Ginsberg [11] describes how different measures of centrality, the importance of node within a network, can be employed to assess how various hazards and vulnerabilities relate each other and their broader risk network. These are summarized in Fig. 1.

Centralities measure how individual risk relate to each other and a risk network, so can be considered the networked equivalent of linear multi-hazard scores derived by assessing probability and impact. The centrality measures of in-degree, out-degree, and degree centrality measure a risk's connections to other individual risks. Measures of



Measure	Description	Use in networked risk assessments
Degree Centrality	The number of edges connected to a single node.	Degree centrality provides a measure of how a risk affects and is affected by other risks in a risk network.
In-Degree	The edges flowing to a single node.	In-degree is a measure of how a risk is affected by other risks within a risk network.
Out-Degree	The edges flowing from a single node.	Out-degree is a measure of how a risk affects other risks within a risk network.
Closeness Centrality	The distance of a node to all other nodes in a network.	Closeness centrality is a measure of how a risk interacts with network cascades.
Betweenness Centrality	How often a node appears as a bridge between nodes in a network.	Betweenness centrality is a measure of how frequently a risk contributes to a network cascade sequence.
Eigenvector Centrality	A measure of a node's influence on an entire network.	Eigenvector centrality measures how a risk influences entire risk networks.

Fig. 1. Centrality measures and risk networks (developed from [11]).

closeness, betweenness, and eigenvector centrality measure a node's geodesic position within the network so illustrate a risk's connections to the overall risk network. Degree centrality measures therefore align to simple linear conceptualizations of risk, while geodesically derived closeness, betweenness, and eigenvector centralities imbed a risk within a network so align to more complex conceptualizations of risk. Of these centrality measures, eigenvector centrality rankings are perhaps the closest networked equivalent to linear hazard rankings since eigenvector centralities are a measure of the overall influence of a node on a network. While eigenvector measures are specifically helpful for comparing results of linear and networked assessments, each of these centrality measurements provides different information on how risk networks function.

Network analysis techniques can also be used to understand the overall structure of risk networks. Measures of how interconnected networks are, or network density measurements, can show how likely risk networks are to cascade. If a risk is realized in a network where all risks are directly connected to each other (e.g. a network with a density of 1) it would create a network-wide cascade across the network. If a risk were realized in a network whose density were closer to 0, it would be much less likely to trigger a cascade. In addition to network density measures, community detection measures can also be used to help understand structures of risk networks. Community detection measures are used to detect communities of nodes that are interconnected through a dense network of edges. When applied to risk networks, community detection can show the specific areas where cascades are likely to occur.

3.2. *Integrating linear and networked risk assessments*

Results of both networked and linear assessments can be expressed numerically, making it possible to aggregate results to create a combined score of each risks that reflects the linear and networked dimensions of risk. Assessments can be considered representational of different dimensions of a risk landscape: the linear assessment as an individualistic view of each risk, and the networked assessmentas a relational view of risk. Given that networked and linear scores convey very different types of information about how risks function, rather than serving to further clarify risks, aggregating assessment results may instead muddle and obfuscate understandings of risk. Thus, scores should remain separated instead of being aggregated, and should be considered in conjunction with each other to provide a more holistic view of risk.

Here we outline a three-stage process for integrate networked and linear risk assessment methodologies based on the common practices of linear and networked assessments.

3.2.1. *Stage 1: Hazard identification*

Hazard identification is the identification of all the hazards in a case of study. Since identifying hazards provides a broad overview of the risk landscape, hazard identification is a common first step to conducting multi-hazard risk assessments. Since risk is not an absolute and hazards differ between levels and groups (individual, community, nation, sector, geographic region, etc.) [14] the unit of analysis being assessed should be clearly specified before beginning the process of identifying hazards. While it is important to specify the unit of analysis when identifying hazards, terms used to describe the properties of disasters such as hazards, vulnerabilities, and root causes, have numerous meanings that are not always useful for networked risk assessments. For instance, Leveson [37] notes that the identification of initiating events and root causes “is arbitrary and previous events and conditions could always be added”. Likewise, vulnerabilities can take on properties similar to hazards, triggering other hazards and vulnerabilities. Given its importance in determining risk, hazard identification can be expanded to include the identification of vulnerabilities, and can be thought of more as the identification of causes and consequences shaping a risk [11] rather than the identification of distinct hazards or vulnerabilities.

3.2.2. *Stage 2: Linear multi-hazard risk assessment*

As previously stated, linear multi-hazard risk assessment is the numeric categorization of hazards by their probability and impact. Assessing hazards by their probability and impact is often the second stage in multi-hazard assessment. Because the probability of the occurrence of a hazard differs depending on length of time, the risk assessment time period should be specified. Time periods could be a unit such as minutes, hours, days, or centuries, or they could be the period of time in a discrete event. It is similarly important to specify how impact should be categorized. Providing a specific and comparable definition of impact can be challenging since impacts are multidimensional, often affecting economic, social, and environmental processes. A common framework should be developed that combines these processes, acknowledging a normative bias toward more easily quantifiable economic risks [51]. Once assessed, probabilities and impacts can be combined to develop overall risk scores, which provide the basis for ranking risks.

3.2.3. *Stage 3: Networked multi-hazard risk assessment*

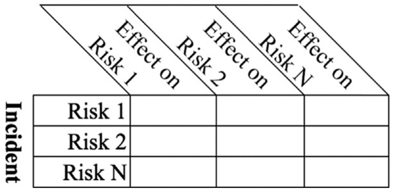
Networked multi-hazard risk assessment is the numeric assessment and comparison of risks based on their networked properties. This involves collecting numeric data on the effect of a risk on other risks, e.g. the directed edges that connect nodes. It is possible to identify risks inductively through the network analysis process using an iterative procedure starting from an initial hazard event [11], but risks can also be selected a-priori based on other functions. Identifying risks through the network analysis process emphasizes the emergent dimensions of risks networks, but focuses on a specific central hazard event rather than the multiple risks identified in a multi-hazard risk assessments. To integrate linear and multi-hazard risk assessments it is therefore useful to select hazards using results of hazard identification and linear multi-hazard risk assessments.

Fig. 2 provides a template for collecting data on the networked dimensions of risk:

This template can be used to collect information on the effect of one risk on another risk. Effect can be a characteristic of probability, impact, or the combination of the probability and impact, but as with Stage 2, it is important to maintain consistency in terminology when collecting data. Effects are equivalent to the edges connecting nodes in a network, so data collected in this format can be used to create an adjacency matrix, from which it is possible to perform network analysis and create network visualizations.

4. Linear and networked risks for businesses operating in Khorasan Razavi Province

Khorasan Razavi Province one of the 31 provinces of Iran. It is located in the northeast corner of Iran, is the sixth largest province in the country by geography, and, with close to six million inhabitants, is the country's second most populated province. Government figures show the province's economy to mainly be a mix of services, industry, and agriculture, with 61% of the economic activities coming from the service sector, 21% from industry, and 16% from agriculture [53].



		Outcome		
		Effect on Risk 1	Effect on Risk 2	Effect on Risk N
Incident	Risk 1			
	Risk 2			
	Risk N			

Fig. 2. Template for collecting networked risk data.

	Score									
Risk	Probability	Impact	Linear Risk Score	Linear Risk Rank	In Degree	Out Degree	Degree Centrality	Closeness Centrality	Betweeness Centrality	Eigenvector Centrality
Aging infrastructure	3.19	2.77	9.11	11	12	1	13	1.00	0.00	0.71
Anti-business regulations and laws	3.99	2.85	11.57	3	8	4	12	0.83	8.00	0.25
Corruption	3.77	2.89	11.38	4	3	8	11	0.79	0.00	0.02
Exchange rate failure	3.50	2.66	9.95	8	5	4	9	1.00	9.00	0.15
Government rent-seeking	3.68	3.02	11.62	2	0	11	11	0.82	0.00	0.00
Groundwater depletion	3.78	3.46	13.24	1	6	6	12	0.73	3.67	0.12
Illegal trade	3.41	2.76	9.94	9	1	10	11	0.81	0.00	0.00
Lack of qualified managers	3.86	2.82	11.17	5	12	2	14	1.00	1.00	0.52
Localized climate change	2.96	2.97	9.28	10	3	5	8	0.70	0.33	0.14
Natural Hazards	2.68	2.68	7.82	13	3	3	6	1.00	0.00	0.17
Noncompliance with international standards	3.41	2.50	9.06	12	14	0	14	0.00	0.00	1.00
Population growth	2.45	2.54	7.17	15	4	7	11	0.71	1.33	0.04
Terrorism	2.62	2.39	7.39	14	1	2	3	0.75	0.00	0.07
Water conflicts and weak customary governance	3.30	2.90	10.05	7	5	7	12	0.75	3.67	0.07
Wealth inequality	3.53	2.92	10.68	6	2	9	11	0.80	0.00	0.01

Fig. 3. Results of risk networked and linear risk assessments.

Approximately 5% of the country's GDP comes from Khorasan Razavi, and the province offers attractions to businesses due to its inexpensive labor force and potential as a religious tourist destination. However, business operating in the province face several risks which align to inhibit economic activities. Some of these are reflections of broader national trends related to the government. For example, the country's fixed exchange rate destabilizes economic activity and creates black markets for currency, and high levels of corruption can reduce competition and add costs to business. Local factors related to the province's infrastructure, customary governance structures, and topography, climate, and flora also influence risk. For instance, as with many mountainous areas, earthquakes are endemic to the region. Additionally, much of the land in the province can be classified as arid and semi arid dryland, a fragile ecosystem often marked by erratic rains, resulting in hazards related to drought, water scarcity and conflict, and environmental degradation.

Data to conduct linear and networked risk assessments of the risks to industrial and agricultural businesses operating in the province was collected over the course of 2014. The following offers a brief description how each of the three stages for integrating assessments outlined in the previous section were operationalized for this case.

4.1. Stage 1: Hazard identification

Several studies have used key informants to identify hazards through brainstorming, focus group discussions, and interviews [22,6]. In addition to providing an overview of hazards, relying on key informants captures a local perspective of risk that aligns with the underlying ontology of networked risk as a locally emergent relational system. To identify the main business hazards in the province we conducted 10 open-ended focus group discussions with stakeholders knowledgeable of the business environment of the province. In total 52 key informants representing the private sector, public sector, and academia participated in these focus group discussions.

In acknowledgement of the importance of vulnerabilities and interconnections between hazards and vulnerabilities, we did not provide guidance on how hazards should be defined in relation vulnerability but instead defined hazards broadly as any incident likely to occur within 15 years and create financial losses for a considerable number of the province's firms (more than 15%). Focus group participants identified a total 121 hazards using this definition.

4.2. Stage 2: Linear multi-hazard risk assessment

The focus group participants from Stage 1 also assessed hazards by their probability and impact. First, to keep the multi-hazard assessment process manageable we narrowed down the hazards to focus on those with the greatest probabilities and impacts. Impact was defined as the ability of businesses to operate at a profitable level. Through semi-structured interviews we developed a list of the 30 hazards that represented the greatest risk based on their probabilities and impact. These were further narrowed down in a series of follow up interviews the top 15 risks based on their probability and impact.

We developed quantifiable probability and impact rankings of these 15 hazards using a nine-point Likert scale paired comparison questionnaire. Likert ranges were defined to be specified and absolutely distinguishable from each other, with probability on a five-point scale, impact on a four-point scale, and overall risk on a 20-point scale derived by multiplying probability and impact. The questionnaire was delivered by a team of trained research students to producers from agricultural and industrial sectors, which we selected using a representative sampling technique. In total, 3117 producers were selected to complete the questionnaire (see Appendix 1 for a list). Overall scores of probability, impact, and overall risk were derived from averaging questionnaire results.

4.3. Stage 3: Networked multi-hazard risk assessment

The producers that we surveyed for the linear probability and impact assessment were also surveyed for the networked risk assessment. We asked respondents to rate the causal relationship between risks on a three-point scale developed in a questionnaire that we developed from the template show in Fig. 2. Results were summated in an overall adjacency matrix, and centrality and density scores were calculated using Gephi, an open source software program for network analysis and visualization. We also used Gephi to produce network visualizations.

4.3.1. Linear and network assessment results

Fig. 3 provides a summary of the results of the linear and networked risk assessments:

The Figure lists top 15 risks, and their associated linear scores (probability, impact, risk score, and risk ranks) and networked scores (in-degree, out-degree, degree centrality, and closeness, betweeness, and eigenvector centralities). The remainder of this section provides a more detailed overview of the assessment results of each stage.

4.4. Stage 1 results: Hazard identification

The 15 main hazards identified by key informants show the diverse array of risks that companies operating in Khorasan Razavi Province must contend with. These include natural hazards, manmade hazards like terrorism, as well as concepts that are often classified of as hazard drivers and vulnerabilities such as population growth, wealth inequality, and aging infrastructure. Hazards do not originate in a single place but are created across scales, with some like groundwater depletion and aging infrastructure stemming from actions at the local level, and others like anti-business regulations and exchange rate failure arising from national processes. Many of these hazards – corruption, government rent seeking, exchange rate failure, and anti-business regulations and laws – are directly associated with government practices, while others are more multi-stakeholder in association.

4.5. Stage 2 results: Linear multi-hazard risk assessment

Probability scores ranged from 2.45 (population growth) to 3.99 (anti-business regulations and laws) on a 5-point scale, impact scores ranged from 2.39 (terrorism) to 3.46 (groundwater depletion) out of 4, and risk scores ranged from 7.17 to 13.24 out of 20. The three risks with the top scores were groundwater depletion (13.24), government rent-seeking (11.62), and anti-business regulations (11.57).

4.6. Stage 3 results: Networked multi-hazard risk assessment

Fig. 4 shows the adjacency matrix derived from the networked questionnaire data:

The matrix shows how strongly risks affect each other. Reviewing the matrix shows there to be a great deal of variation in the degree of effect of one risk on another. Certain risks were viewed as having a strong effect on other risks: with a total score of 893, water conflicts and weak customary governance were viewed as having a strong effect on groundwater depletion, as did government rent-seeking on corruption, as seen by its score of 852. Less than half of the connections between nodes that could be made, however, were made: of the 225 possible edges in the matrix, 141 had a score of 0, leading to an overall network density of 0.38.

This matrix can be visualized as a network (Fig. 5). Edge width and shade are based on weight of connections between risks, and nodes are shaded by community and weighed by eigenvector centrality. Blondel et al.'s [5] algorithm for community detection was employed to detect two risk communities, one made up of 9 risks and another a comprised of 6 risks. The larger community broadly contains human derived hazards, many of which are related to governmental policies and practices, while the smaller community is primarily comprised of naturally related hazards less-directly associated with the procedures of the state. Connections do exist between these two communities, but risk cascades are likely to occur within rather than between communities.

Degree centrality measures show how risks are connected to each other. Noncompliance with international standards had the highest in-degree score of 14, indicating many risks contribute to noncompliance with standards, and government rent seeking had the highest out-degree score of 11, indicating it affects many other business risks. With scores of 14, lack of qualified managers and noncompliance with international standards had the highest degree centrality scores, showing that these risks are highly connected with other risks.

Geodesic centrality measures show how risks connect with their network. Lack of qualified managers, aging infrastructure, exchange rate failure, and natural hazards had the highest closeness centrality measures of 1, indicating that they are often parts of risk cascades. Exchange rate failures and anti-business regulations and laws had the highest betweenness centrality measures of 9 and 8 respectively. These risks often contribute to cascade sequences. Noncompliance with international standards had the highest eigenvector centrality score (1) followed by aging infrastructure (0.71), and lack of qualified managers (0.52). While high eigenvector scores indicates the prominence of these three risks from a networked perspective, with ranks of 12 and 11 respectively, noncompliance with international standards and aging infrastructure – with ranks of 12 and 11 respectively – are both in the bottom third of linear risk rankings, while with a rank of 5, lack of qualified managers is narrowly in the upper third of linear rankings.

5. Discussion and conclusion

In this article, we provided a theoretical and empirical comparison of linear and networked approaches to disaster risk assessment. We began by distinguishing between the conceptual foundations of networked and linear assessments, showing that networked approaches

	Outcome														
Incident	Aging infrastructure	Anti-business regulations and laws	Localized climate change	Corruption	Natural hazards	Exchange rate failure	Government rent-seeking	Groundwater depletion	Illegal trade	Lack of qualified managers	Noncompliance with international standards	Population growth	Terrorism	Water conflicts and weak customary governance	Wealth inequality
Aging infrastructure	0	0	0	0	0	0	0	0	0	0	66	0	0	0	0
Anti-business regulations and laws	500	0	0	0	0	595	0	0	0	772	679	0	0	0	0
Localized climate change	573	330	0	0	563	0	0	0	0	280	286	0	0	0	0
Corruption	313	679	0	0	0	544	0	227	0	806	629	300	0	315	0
Natural hazards	520	0	0	0	0	0	0	0	0	90	520	0	0	0	0
Exchange rate failure	272	0	0	0	0	0	0	0	0	590	552	0	90	0	0
Government rent-seeking	360	706	0	852	0	551	0	260	773	708	588	265	0	294	725
Groundwater depletion	557	340	817	301	0	0	0	0	0	380	526	0	0	0	0
Illegal trade	319	700	0	835	0	520	0	254	0	645	588	291	0	260	751
Lack of qualified managers	405	0	0	0	0	0	0	0	0	0	690	0	0	0	0
Noncompliance with international standards	0	0	0	0	0	0	15	0	18	12	0	0	0	6	0
Population growth	325	348	359	0	0	0	0	670		328	312	0	0	528	0
Terrorism	0	0	0	0	0	0	0	0	0	495	280	0	0	0	0
Water conflicts and weak customary governance	425	325	660	0	290	0	0	893	0	384	378	0	0	0	0
Wealth inequality	316	613	0	796	0	490	0	272	0	614	486	444	0	310	0

Fig. 4. Adjacency matrix of networked risks.

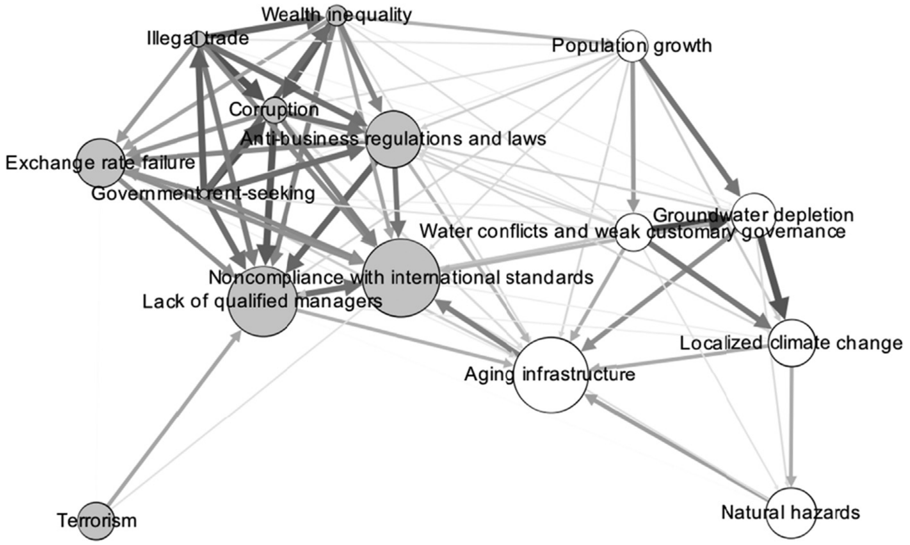


Fig. 5. Map of networked risks, with node sizes weighted by eigenvector centrality and shaded by community.

reflect a complex non-linear ontology of the world that differs from simple linear ontology underlying linear assessments. We argued that while a complex ontology poses challenges for operationalizing networked assessments, in keeping with the pragmatist orientation of disaster studies, networked and linear assessments can be used together as long as results improve understandings of risk. We then demonstrated how networked and linear assessments can be combined through an empirical case, the risks to businesses operating in Khorasan Razavi Province. We found that risk rankings differ depending on whether risks were assessed using networked or linear assessments.

The results of the empirical case illustrate how networked and linear approaches can be used together as part of an overarching risk assessment. Assessing risks by probability and impact is useful for ranking risks on their own while network analytic techniques highlight the various functions of risks in their network. This includes how risks are affected by and affect other risks (in-degree and out-degree), their likelihood of being involved in a cascade (closeness centrality) and their importance in instigating or maintaining cascades (eigenvector centrality). Network analysis also helps understand the overall risk network, revealing where hazard cascades are likely to occur (community detection) and indicates the chances for network-wide cascades (network density).

Results of our network assessment support many of the commonly understood interactions found in the disaster literature. In our risk network, social risks mainly related to actions of the state such as corruption, anti-business regulations and laws, and exchange rate failure formed one system of risk, and environmental risks related water conflicts, aging infrastructure and climate change formed another. The divisions we identified are similar to how other systems have been divided, such the Sustainable Livelihood Framework [48] which divides asset classes into interacting social, natural, economic, political, and human systems. Aging infrastructure is a potential bridge between our two systems, evidenced by its high centrality score and its position near both systems. This supports the idea that critical infrastructures play an orienting function in cascades since they have both physical and social dimensions [45]. The bridging function of infrastructure was not captured in linear assessments, which ranked aging infrastructure in the lower third of risks. We also found factors typically considered vulnerabilities feature heavily in the risk landscape of Khorasan Razavi Province. For instance, the three risks with the highest eigenvector centralities, noncompliance with international standards, aging infrastructure, and lack of qualified managers, are closer to vulnerabilities and risk drivers than they are to hazards. Likewise, traditional hazards like terrorism and natural hazards featured only peripherally in our risk assessment. This supports Pescaroli and Alexander's [45] findings of importance of vulnerability in shaping disaster cascades and suggests reorienting networked risk assessments to focus on vulnerability.

While this article offers clarifications on how networked and linear risks relate, there were also limitations to conducting networked risk assessments. Our networked risk assessment did not provide a complete representation of a risk interactions but instead artificially-bounded risk networks to the top 15 risks. Had we assessed the networked relations of all 121 risks, resulting risk rankings may have differed. Our assessments also treated the risks as a closed system, while in reality they functioned as an open system: exchange rate failures, for instance, are a product of national monetary decisions coupled with changes in the international global economy. Even if we had the resources to assess this open system in its entirety, interconnections would still be missed because knowledge on the ways that risks connect are still not yet completely known [17,38]. Furthermore risk systems demonstrate emergence, so will never be completely knowable [10,37]. While our network risk assessment process helps identify system interactions it did not capture emergence or the ways in which systems might radically transform. Although our artificially bounded system and inability to account for emergence presents affects the accuracy of the risk assessment process, we do not go so far as to suggest abandoning efforts to assess risks for complex systems. Instead, we advocate that networked risk assessments should be undertaken with an awareness of the uncertainties and limitations in knowledge inherent to any assessments of complex systems.

Our results suggest that certain strategies may be more effective than others for managing risk. The networked nature of risk demands a networked approach to risk management, whereby different stakeholders coordinate to prevent the realization and spread of known hazards and vulnerabilities across systems. Given their centrality in propagating risks, particular focus should be paid to mitigating vulnerabilities as part of a broader risk prevention strategy. While improved mitigation can help prevent the realization of known risks, since networked assessments are not able to capture every element of risk, unexpected crises will inevitably arise even if comprehensive prevention strategies are put into place. Thus, resilience should be included as a risk management approach, and efforts should be made to improve the ability of stakeholders to react to, recover from, and transform in the face of crisis.

A few additional areas of research can be identified from this study that could improve how networked risks are assessed and managed.

Research should be undertaken on how risk rankings of the same risk networks change if networks are represented in different levels of detail. It may be that certain risks have many connections with numerous low impact and low probability risks that only become manifest when risk networks are sufficiently detailed. This type of research could clarify how placing different boundaries on risk networks affects the outcome of risk assessments and could help determine the level of detail necessary to represent coupling and complexity of different systems. Efforts also need to be made to understand how networked resilience can be assessed in relation to networked hazard and vulnerability cascades. Along with providing the potential for cascades, networks are a source of strength for critical infrastructures, allowing for rapid recovery from crisis [16]. Assessment mechanisms that integrate networked risk and networked resilience could be developed to help understand the co-constitutive nature of resilience and risk. All of these new assessment techniques need to be empirically tested and validated. Assessing whether networked risk assessments match the actual cascades that occur during disasters can provide a process for further refinement of assessment tools by uncovering their strengths and weaknesses.

Appendix 1. Respondent sample

Sector	Population (Number of firms)	Percentage of the firms in the sector	Sample (number of firms)
Agriculture business environment			
manufacture of food and beverages	4433	40.21	267
Manufacture of chemicals and chemical products	1675	15.20	210
Manufacture of rubber and plastics products	1101	9.99	137
Manufacture of other non-metallic mineral products	1602	14.531	184
Manufacture of fabricated metal products, except machinery and equipment	814	7.38	173
Manufacture of machinery and equipment n.e.c.	445	4.03	221
Manufacture of electrical equipment	445	4.03	171
manufacture of textiles	509	4.61	158
Agriculture business environment			
Crop production	165777	60.02	904
Horticulture	69693	25.23	285
Poultry	1083	0.39	226
Livestock	39631	14.34	181

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