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Modelling the complexity of the network of interactions in flood emergency management: The Lorca flash flood case

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ABSTRACT

There is growing awareness that fast response to emergency situation requires effective coordination among several institutional and non-institutional actors. The most common approaches, based on innovating technologies for information collection and management, are not sufficient to cope with the increasing complexity of emergency management. This work demonstrates that effective cooperation claims for a shift from information management to interaction management. Therefore, methods and tools are required in order to better understand the complexity of the interactions taking place during an emergency, and to analyse the actual roles and responsibilities of the different actors. This paper details the design and implementation of an integrated approach aiming to unravel the complexity of the interaction network based on Storytelling, the Problem Structuring Method, and Social Network Analysis. The potential of the integrated approach has been investigated in the Lorca (Spain) flood risk management case study.

Software availability

Program name: *ORA-NetScenes
COPYRIGHT (c) 2001-2016: Kathleen M. Carley
Contact address: Center for Computational Analysis of Social and Organizational Systems (CASOS) Institute for Software Research (ISR), School of Computer Science - Carnegie Mellon University - 5000 Forbes Avenue Pittsburgh, PA 15213-3890
Creation year: 1995
Year available version: 2016
Version used: ORA 3.0.9.9.36 (June 2016)
Program language: Java GUI and C++ backend
Software availability: Permission to use this version of the software or any parts of it and to use, copy, or modify its documentation is hereby granted for research and teaching only purposes. Commercial and governmental licensing of the software is available by contacting Dr. Kathleen M. Carley (kathleen.carley@cs.cmu.edu).

Hardware Requirements
- CPU with 500 megahertz or higher processor clock speed recommended (3 Ghz is ecommended for large datasets) Intel Pentium/Celeron family, or AMD K6/Athlon/Duron family, or compatible processor recommended
- 512 MB of RAM or higher recommended (1 GB preferred)
- 500 MB of available hard disk space

1. Introduction

Over the last few years, a number of natural disasters have demonstrated the need for quick and effective responses, to minimize the number of deaths and injuries, as well as the financial cost associated with damage and losses (Luokkala and Virrantaus, 2014; O'Sullivan et al., 2013; Seppänen and Virrantaus, 2015). Response needs to be provided under the severe stress of crisis conditions,

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and requires the coordinated involvement of experts and organizations from several fields (Katuk et al., 2009). Nowadays, the response to crises becomes an emerging, large-scale, socio-technical system of individuals, groups, organizations and jurisdictions that need to coordinate their actions for delivering effective operations (Hardy and Comfort, 2015; O'Sullivan et al., 2013). No single entity has complete control of these multi-scale, distributed, highly interactive networks, or the ability to evaluate, monitor and manage emergencies in real time.

Enhancing the coordination effectiveness of different responders has been considered from multiple perspectives such as lack of cross-sectors structures, lack of common goals, lack of common concepts, lack of distribution of information, lack of trust, complex accountability issues, inequalities of power and struggles for dominance, legacy issues, different perception of the collaboration, and lack of situational awareness (e.g. Aldunate et al., 2005; Comfort, 1999; Danielsson and Ohlsson, 1999; Kapucu et al., 2009; Moynihan, 2008; Hardy and Comfort, 2015; McMaster and Baber, 2012; Seppänen et al., 2013). Most of these studies suggested that involved agencies claimed for a fast though-smooth and well-structured distributed and collaborative decision-making process (Brehmer, 1991; Cosgrave, 1996; Smith and Dowell, 2000). Nevertheless, the implementation of collaborative decision-making approaches (i.e. Hills, 2004; Raiffa, 2002; Turoff et al., 2008) has received limited attention (Kapucu and Garayev, 2011). This is mainly due to the existing gaps between the traditional emergency management methods characterized by centralization and hierarchy-based structures and the actual collaborative management process, characterized by non-hierarchical structure and flexibility (Kapucu and Garayev, 2011).

Furthermore, the capabilities of organizations to overcome the fractured nature of information in distributed system, through an effective information exchange by collaborative agents gained a lot of interest (Sorensen and Stanton, 2013; Comfort and Haase, 2006; Comfort, 1999). It is crucial that the right agents receive the right information at the right time (Calderon et al., 2014). Most of the efforts carried out for enhancing coordinated information management were meant to innovate the information technology for internal and external communication, information production and sharing (Luokkala and Virrantaus, 2014; Leskens et al., 2014). Several authors emphasize the inadequacy of these information management systems (Endsley et al., 2015; Leskens et al., 2014; Luokkala and Virrantaus, 2014; McMaster and Baber, 2012; Seppänen et al., 2013; Wolbers and Boersma, 2013). Firstly, these systems seem inadequate to cope with the dynamic nature of the emergency management process. Information management and sharing procedures within a responding organization and/or among different organizations might be jeopardized by the need to alter organization structure and roles, procedures and use of information in order to meet the demands of an exceptional event, such as an emergency situation (McMaster and Baber, 2012). Moreover, interaction networks change dramatically during an emergency leading to the creation of temporary multi-organization (Cherns and Bryant, 1984). The role of the different agents in the interaction network and the tasks they have to perform could change during a crisis. The existing emergency information management systems and the institutional protocols for information management in case of emergency seem to be incapable of adapting themselves to this changing interactional situation.

Secondly, evidences demonstrate that implementations of information management and communication technologies failed in many situations because of the oversimplification of the social processes at the base of emergency information management (McMaster and Baber, 2012). This has also been true for cases where innovative technology has been used (e.g. internet-of-things, smartphone, smart city cameras and stoplights, etc.). The key steps in the process of transforming risk information and warning into actions – i.e. hearing, understanding, believing, personalizing and deciding – are mediated through social structures. Exposing all individuals to the same information in the same way, without accounting for the different social structures, might affect the ability to generate novel ideas and interpretations of the emergency situation (Smart and Sycara, 2013; Leskens et al., 2014).

Effective cooperation for emergency management requires a shift from innovating information production and management technologies toward enhancing the interaction processes among actors involved in emergency management (Kapucu and Demiroz, 2017). Interaction represents the mechanism allowing the different actors to interpret their environment, to achieve a satisfactory shared understanding of the situation – i.e. sensemaking process (Wolbers and Boersma, 2013) – and to cope with the organizational and individual improvisation needed to deal with extreme events (Maitlis, 2005; McMaster and Baber, 2012). Enhancing the interaction among the different actors is a *sine-qua-non* condition to mitigate the conflicting interpretation of information about emergency due to differences in knowledge belief, customs and assumptions (Wolbers and Boersma, 2013), and to enable the knowledge processing and regenerating process, involving different teams and members of the same team with different background (Hardy and Comfort, 2015; Seppänen et al., 2013).

This work argues that a collaborative emergency management requires tools and methodologies capable of creating a decision-making environment in which parties are fully aware of their role and the roles of the others in the interaction space, according to the interdependency principle (Gray, 2004).

Emergency management network are more emergent than planned (Kapucu and Demiroz, 2017). This means that, although these networks are not completely independent from previously established relationships, they do not follow pre-emergency arrangements. Therefore, the analysis of the emergency management network cannot be based on existing and formalized relationships. Informal interactions are activated, and non-institutional actors play crucial roles in responding to the emergency. Keeping tracks of these interactions is difficult, hampering the capabilities of analysts and researcher to implement formal methods for the analysis of the interplay of factors influencing the network effectiveness – e.g. actors, knowledge, resources and tasks (Kapucu and Demiroz, 2017). Moreover, although existing quantitative methodologies, such as Social Network Analysis, offer conceptual and methodological tools for explaining macro-level structural patterns in the interaction networks (Schipper and Spekkink, 2015), the comprehension of the dynamic nature of the emergency management network cannot neglect the role of micro-level – i.e. agent level – behaviours.

In order to address the above mentioned issues, a methodology based on the integration among the Storytelling approach (Boyce, 1995; de Bruijn et al., 2016), Problem Structuring Methods (PSM) and Social Network Analysis (SNA) has been adopted. This work aims at demonstrating that the integration between SA and PSM allows integrating the macro- and the micro-level in analysing and unravelling the complexity of the emergency network. The central research question of this article is: to what extent the integration between the PSM capabilities to collect and structures individual behaviours, and SNA quantitative measures for describing the macro-properties of the network is suitable to support emergency managers in identifying barriers to the cooperation and collaboration (Bodin and Crona, 2009), and in defining potential improvements of the emergency management procedures? To this aim, this work evaluates the suitability of the PSM-SNA integrated modelling approach to create salient and credible knowledge system to stakeholders, and motivate legitimate decision-making and consequential actions (Muñoz-Erickson, 2014; Wesselink et al., 2013).

The developed methodology has been experimentally implemented in the Lorca case study (Spain), to analyse the complexity of the interaction network which emerged during the last episode of flash flooding (2012). This contribution is structured as follows. After the present introduction, providing details on the theoretical background, section 2 discusses the methodology applied. Sections 3 illustrates the Lorca case study. Section 4 and 5 describe and discuss the obtained results and the lessons learned. Concluding remarks are described in section 6.

2. Material and methods

2.1. General

In order to demonstrate our research hypothesis, the implemented methodology is structured in two main phases:

- Collection and structuring of the local and experts' knowledge about the interactions – both formal and informal – taking place during the emergency management process: in this phase a sequential implementation of Storytelling Approach and Problem Structuring Method, specifically Fuzzy Cognitive Mapping (FCM), was implemented. The FCM allowed the translation of collected narratives into useful inputs for the SNA.
- Mapping and analysing the complexity of the interactions: the SNA was used to better comprehend the actual role played by the different actors – both institutional and non-institutional – in case of emergency, the tasks performed and the information each actor brings into the network. The quantitative SNA measures allowed identification of the potential vulnerabilities in the emergency interaction network.

The following sections describe these two phases, the implemented methodologies and their contribution to the achievement of our overall goal.

2.2. Knowledge elicitation and structuring

In order to develop the interaction network model, both experts' and local knowledge was collected in this phase, mainly concerning: i) the emergency management, ii) the role of information exchange, and iii) the interactions taking place during a crisis. The adopted approach for knowledge elicitation is based on the assumption that a particular section of knowledge, either deriving from experts or community members, is equally important (Mackinson, 2000). In this work, we use the term "experts" to indicate policy-makers and official responders involved in the emergency management. The experts' knowledge was elicited through a series of individual semi-structured interviews. A participatory modelling exercise was designed for collecting community's knowledge. In both phases, a Storyline Approach (SA) was implemented, allowing to increase the insight in the sequence of events during a flood event (de Bruijn et al., 2016). The storyline approach is based on a few steps: i) description of the system being investigated (e.g. flood prone areas, potential impacts, flood management procedures/protocols and key actors involved); ii) definition of a scenario, referring to a specific flood episode; iii) determination of the sequence of events during a storyline. The key actors were involved (local authorities, first responders and inhabitants). The focus was mainly on actions and responses implemented by each actor in order to achieve their goals in the emergency management, the information used and the other agents with whom they interacted; iv) analysis of the storylines, involving the physical changes as well as the timing and type of responses of the actors. This phase was mainly oriented at revealing the impacts of the external pressure and the effects of actions of local authorities and inhabitants on these impacts.

The interviews were conducted taking into account the main advantages and drawbacks of the approach (de Bruijn et al., 2016): interviews must be detailed enough to reconstruct the sequence of events; the approach helps identifying which assumptions are relevant and the existing knowledge gaps; it is fundamental to point interdependencies and complexity.

The first issue to be addressed concerned the selection of the experts to be involved in this phase. In order to minimise the selection bias and the marginalization of stakeholders (Ananda and Herath, 2003; Reed et al., 2009) a top-down stakeholder identification practice, which is referred as "snowballing" or "referral sampling", was implemented (Harrison and Qureshi, 2000; Prell et al., 2008; Reed et al., 2009). The selection process started with the actors mentioned in the official protocols of intervention. The preliminary interviews carried out with these agents allowed us to widen the set of stakeholders to be involved.

In order to inform/protect participants to the study, an informed consent form was prepared and shared. Particularly, the form included: i) a general summary of the purpose of the research project and, more specifically, of the interviews; ii) possible risk/discomforts associated to the interview and potential benefits for the interviewee; iii) the possibility of withdrawing at any time from the study; iv) the confidentiality of personal data and information, also in case of scientific publication.

The results of the interviews were structured in individual Fuzzy Cognitive Maps (FCM) (Eden, 2004; Eden and Ackermann, 2004) (Fig. 1). The structuring phase allowed us to translate the narratives into useful inputs for the SNA phase.

The interactions with the other agents can be activated through both the sharing of information and the cooperation to perform specific tasks. Each link in the FCM is characterized by a weight, which describes the stakeholders' perception of the importance of that connection (Borri et al., 2015). The weight of the link *agent-information* describes the interviewee's perception about how

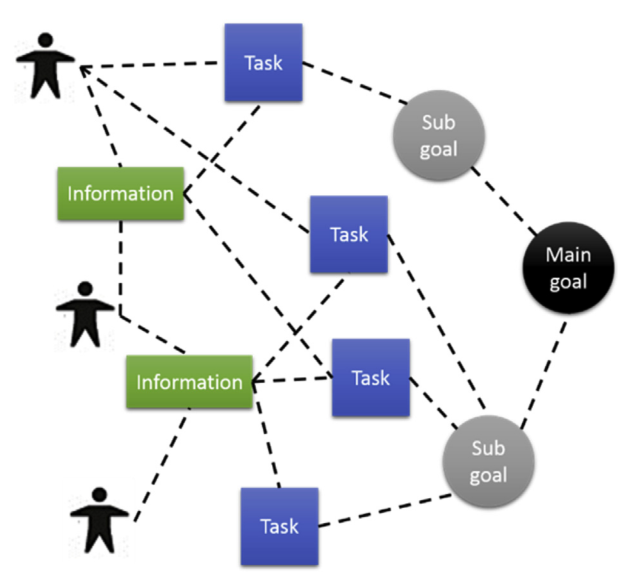

Fig. 1. Fuzzy Cognitive Map describing the individual's understanding of the connections between goal-task-information-agents.

relavant is the agent to obtain the needed information. Similarly, the weight of the link *information-task* represents the role played by the information in facilitating the implementation of that specific task. In order to facilitate the elicitation of the participants' opinions about the importance degree, fuzzy linguistic variables were defined. The methods described in (Krueger et al., 2012; Page et al., 2012; Pagano et al., 2014) have been implemented. Considering that these variables described labelled impressions, i.e. human judgement, rather than a set of mathematically well-defined objectives, and did not have a numeric base variable, the method described in (Giordano and Liersch, 2012a) was used to develop the membership functions for these linguistic variables. This method requires the identification of the linguistic labels used by the interviewees to describe the importance of the connections. Two semantic labels were used to describe the connection *agent-information*, i.e. “exclusive” and “limited”. That is, the agent had exclusive/limited access to the information. Similarly, the *information-task* connection was assessed by the experts as “supporting”, “important” and “indispensable” (Fig. 2).

Individual FCM representing the experts’ understandings of the complexity of the network of interactions were developed.

The knowledge elicitation phase was then completed with the involvement of members of the local communities in a participatory modelling exercise, aiming at eliciting and structuring the community's understanding of the emergency management process. During the first round of the modelling exercise, the participants were required to start providing their individual inputs concerning the other members of the community, institutional organizations and official responders with whom they interacted during the last emergency situation. To facilitate the interaction, a set of icons representing the main actors was created. In the second round, participants were required to describe the information collected during the emergency management and to link this information to the actors, both institutional and non, described in the previous phase. Participants were also required to assign a degree of importance to each interaction. A debate was carried out among participants in order to facilitate the synthesis among the different points of view. Finally, participants were required to describe how the collected information lead to actions (tasks) carried out as emergency responses.

At the end of this phase, the FCM representing the participants’ understanding of the interaction network involving the community during an emergency was developed.

2.3. Mapping the network of interactions: the meta-matrix approach

The Social Network Analysis (SNA) method was implemented in this phase. SNA investigates the social relationships of a large number of actors between different groups of organizations and provides a mathematical approach for measuring the strength of ties (Furht, 2010). In this work, SNA phase focused on structural patterns between actors involved in emergency management, allowing the understanding of roles, interdependencies, tasks, and information flows, through specific measures.

Specifically, SNA has been implemented to make explicit the informal networks of interactions, allowing emergency managers to better comprehend its complexity and enhance their capabilities to manage the emergency network. Among the different methods available in the scientific literature for modelling and analysing the

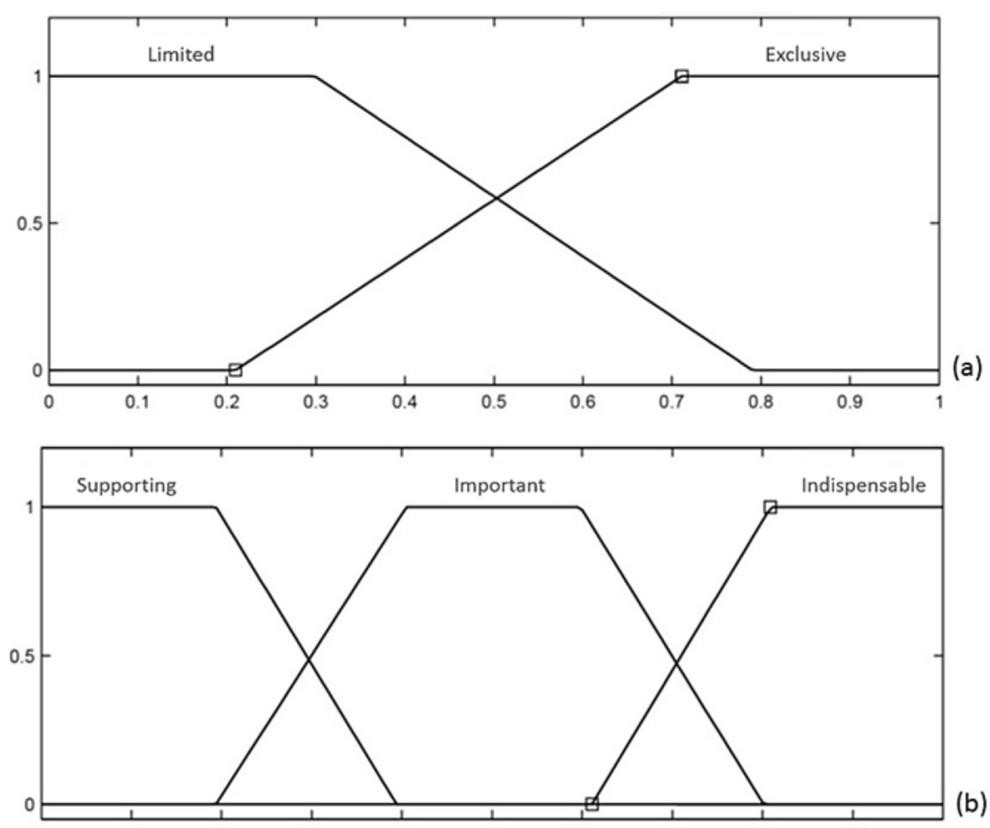

Fig. 2. Fuzzy Linguistic variables: (a) agent-information; (b) information-task.

social networks (e.g. Borgatti, 2006; Ingold, 2011; Lienert et al., 2013), the Organizational Risk Analysis (ORA) approach has been implemented in this work (Carley, 2002). The underlying assumption in ORA is that an organization could be conceived as a set of interlocked networks connecting entities such agents, knowledge, tasks and resources (Carley, 2005). In order to implement this approach, we considered the whole set of actors involved in flood risk management as one heterogeneous organization (Leskens et al., 2014). The interlocked networks can be represented using the meta-matrix conceptual framework, as shown in the following Table 1.

The ORA method theorizes that the effectiveness of a social network is not limited to the way the different actors interact with the others. The meta-matrix framework allows to analyse the complexity of the emergency interaction network accounting for the role of knowledge and tasks, and of the interconnections among the key elements – i.e. agent, knowledge and tasks.

The *Agent* × *Agent* matrix is shown in the Table 2.

In the previous matrix, W_{ij} represents the importance of the interaction between the agent A_i and the agent A_j as perceived by the agent A_i. Similarly, the value of W_{ji} refers to the strength of the interaction between the agent A_i and the agent A_j as perceived by the agent A_j. The weights were calculated referring to the results of the knowledge elicitation phase (section 2.2). Considering that in the FCM the *Agent* × *Agent* interaction is mediated through information, tasks and goals, the aggregation between the importance degrees of the *agent-information*, *information-task* and *task-goal* links in the FCM was used to assess the weights in the matrix. That is, we assumed that the extent to which A_i considered important the interaction with A_j depends on the information A_j could provide in order to allow A_i to perform the allocated tasks and achieve the specific goal. Fuzzy *if … then* rules and the defuzzification operator were implemented to define the weights for the *Agent* × *Agent* matrix (Giordano and Liersch, 2012a). A row vector was obtained for the i-th agent: $W_i = (w_{i1}, w_{i2}, w_{i3}, \ldots, w_{in})$. The *Agent* × *Agent* matrix was obtained combining the individual row vectors.

The individual FCMs were also used to define the other matrices. For instance, the individual i-th *Agent* × *Knowledge* matrix was obtained considering the weights assigned by the i-th actor to the different *agent-information* connections. The *Agent* × *Knowledge* matrix for the i-th agent is represented in the Table 3.

The overall *Agent* × *Knowledge* matrix was obtained as the sum of the individual matrices. Similar processes were implemented to develop the *Agent* × *Tasks*, *Knowledge* × *Knowledge*, *Knowledge* × *Tasks* and *Tasks* × *Task* matrices.

2.4. Analysing the network of interactions: the graph theory measures for vulnerability assessment

The aggregation of the different matrices allowed us to obtain the meta-matrix and, thus, the map of the interactions taking place during an emergency and connecting agents, knowledge and tasks. The map was developed using the ORA© software (Carley, 2005), developed by the Centre for Computational Analysis of Social and Organizational Systems of the Carnegie Mellon University. Following the graph theory, the weights in the matrixes were used to represents the strength of graph edges, while rows and columns were labelled by graph vertices. Indeed, a graph $G = <V, E>$ consisting of a set of vertices (nodes) V and a set of edges (arcs) E, can be represented by an adjacency matrix $A = |V| \times |V|$.

In this work, the map of the network was used to analyse and unravel the complexity of interactions, allowing the identification of the key elements in the network and the main vulnerabilities. To this aim, graph theory measures were implemented. Table 4 describes the measures adopted for the identification of the key actors, their definition according to the graph theory and the meaning in emergency management. For a detailed description of the graph theory measures for the analysis of the networks, a reader could refer to (Freeman, 1978; Carley et al., 2007).

Different measures are mentioned in the scientific literature for the assessment of the network vulnerability, that is, those elements that could lead to failures of the network, lower performance, reduced adaptability, reduced information gathering, etc. (e.g. Carley, 2005). Considering the complexity of the emergency network, in this work the vulnerability elements were identified though the combination of different measures, as described in the Table 5.

3. Case study description: flash flood management in Lorca (Spain)

The described methodology was implemented to analyse the interaction network supporting the flood emergency management in Lorca and Puerto Lumbreras municipalities, located in the Murcia

Table 2
Agent × *Agent* matrix.

	A_1	A_2	A_3	…	A_n
A_1	0	W_{12}	W_{13}	…	W_{1n}
A_2	W_{21}	0	W_{23}	…	W_{2n}
A_3	W_{31}	W_{32}	0	…	W_{3n}
…	…	…	…	0	…
A_n	W_{n1}	W_{n2}	W_{n3}	…	0

Table 3
Knowledge network matrix for the i-th agent.

	I_1	I_2	I_3	…	I_n
A_1	K^i_{11}	K^i_{12}	K^i_{13}	…	K^i_{1n}
A_2	K^i_{21}	K^i_{22}	K^i_{23}	…	K^i_{2n}
A_3	K^i_{31}	K^i_{32}	K^i_{33}	…	K^i_{3n}
…	…	…	…	…	…
A_n	K^i_{n1}	K^i_{n2}	K^i_{n3}	…	K^i_{nn}

Table 1
Meta-matrix framework showing the connections among the key entities of social network (adapted from (Carley, 2005)).

	Agent	Knowledge	Tasks
Agent	*Social network:* map of the interactions among the different institutional actors in the different DRR phase	*Knowledge network:* identifies the relationships among actors and information (Who does manage which information? Who does own which expertise?)	*Assignment network:* defines the role played by each actor in the DRR phases
Knowledge		*Information network:* map the connections among different pieces of knowledge	*Knowledge requirements network:* identifies the information used, or needed, to perform a certain task in the DR
Tasks			*Dependencies network:* identifies the work flow. (Which tasks are related to which)

Table 4
Graph Theory measures for key element detection.

Network	Network measure	Assessment	Meaning in DRR
Agent × Agent	Total degree Centrality	Those who are ranked high on this metrics have more connections to others in the same network.	Individuals or organizations who are 'in the know' are those who are linked to many others and so, by virtue of their position have access to the ideas, thoughts, beliefs of many others.
	Betweenness centrality	The betweenness centrality of node v in a network is defined as: across all node pairs that have a shortest path containing v, the percentage that pass through v.	Individuals or organizations that are potentially influential are positioned to broker connections between groups and to bring to bear the influence of one group on another or serve as a gatekeeper between groups.
Agent × Knowledge	Most knowledge	Assess the number of links between a certain agent and the different pieces of knowledge in the network.	An agent with a high value of most knowledge has access to a great variety of knowledge to be used in case of disaster.
Agent × Task	Most task	Assess the number of links between a certain agent and the different task that need to be carried out in case of emergency.	An agent with a high degree of most task plays a crucial role in the network due to her/his capability in performing different tasks.
Knowledge × Knowledge	Total degree of centrality	It calculates the importance of a certain piece of information according to the number of connected links.	The most central pieces of knowledge are those whose availability is crucial to make the other pieces of knowledge accessible.
	Closeness centrality	Closeness is the inverse of the sum of distances in the network from a node to all other nodes.	The closeness centrality measure allows us to identify the information that could facilitate the process of information sharing.
Knowledge × Task	Most task	Assess the number of links between a certain piece of knowledge and the different task that need to be carried out in case of emergency.	The pieces of knowledge with a high value for this measure are fundamental for the effectiveness of the network, since without them a high number of tasks will be not carried out.
Task × Task	Total degree of centrality	It analyses the complexity of the connections within the task X task network.	Tasks with high degree of centrality are those that have to be carried out in order to allow the executions of the other tasks.

autonomous region (South - Eastern Spain). The study area is characterized by a high-risk level associated to natural disasters, mainly floods, but also droughts and earthquakes. Lorca is the third city within the Murcia region and the main one in the shire of Alto Guadalentín, a large valley that has turned into one of the most important agricultural areas in Spain. Paradoxically, the area is characterised by a semi-arid climate.

The area has historically suffered serious disaster episodes. Specifically, the Lorca – Puerto Lumbreras area is one of the areas more prone to hazardous events of the region, as proven by some major events such as Puerto Lumbreras flood in 1973 and St. Wenceslas Flood in 2012. These events caused several fatalities and damages to buildings and infrastructures (e.g. Puentes dam was destroyed twice by flooding).

Flooding episodes typically occurring in the area may be extremely dangerous due to their quick onset: the flow rate can increase in minutes up to 2000 m^3/s, conveying in two hours approximately the same volume of water that is normally expected in a whole year. Specifically, in the flash flood event of the 2012, the Nogalte wadi, a tributary to Guadalentín river, changed from a dry riverbed to a wide and fast-flowing river in less than 20 min (Fig. 3).

In order to cope with flash flood emergencies, a protocol of interactions was developed aimed at facilitating the coordination and the flow of information among the different institutions and official responders. Fig. 4 schematizes the official protocol of interactions in case of emergency in the Murcia autonomous region.

As shown in the figure, the protocol assumes a hierarchical structure concerning the flow of information. One of the tasks of the Spanish Meteorological Institute (AEMET) is to disseminate the early warning based on the weather forecasts. According to the level of warning – i.e. red, orange and yellow – actions are taken by the Murcia emergency management unit (Murcia 112). During the flood event, two independent monitoring networks collect data. That is, the rainfall monitoring system provides real time data to the Murcia 112. The SAIH, the Segura River Basin monitoring system, provides accurate and updated data on the rainfall, the level of the water in the riverbeds and the level in the reservoirs. These two monitoring systems do not exchange and integrate information.

Table 5
Measures for the detection and analysis of key vulnerability in the emergency management network.

Network	Network measures	Meaning in emergency management
Agent × Agent Agent × Knowledge	Total centrality degree Most knowledge	An actor with a high degree of centrality and a low most knowledge degree represents a vulnerability because, although she/he a central position in the network, she/he has a limited capability to enable information sharing.
Agent × Agent Agent × Knowledge	Betweennes centrality Most knowledge	An actor with a high degree of most knowledge and a low betweennes degree represents a vulnerability because she/he is not capable to share with the others the pieces of knowledge she/he has access to.
Agent × Agent Agent × Task	Total centrality degree Most task	An actor with a high degree of most task and a low centrality degree represents a vulnerability because, although she/he is required to carry out important tasks, she/he is quite isolated and cannot be supported by the others during an emergency.
Agent × Knowledge Knowledge × Task	Most knowledge Most task	A piece of knowledge poorly shared within the network (low most knowledge) represents a vulnerability if its access is crucial to carry out important task (high most task).
Agent × Knowledge Knowledge × Knowledge	Most knowledge Closeness centrality	A piece of knowledge with a high degree of closeness but poorly shared (low degree of most knowledge) represents a vulnerability since it could hamper the process of information sharing.
Agent × Task Task × Task	Most task Centrality degree	A task with a high centrality degree and with low ost task degree represents a vulnerability because, although its importance, there is no, or very limited cooperation to guarantee its effectiveness.

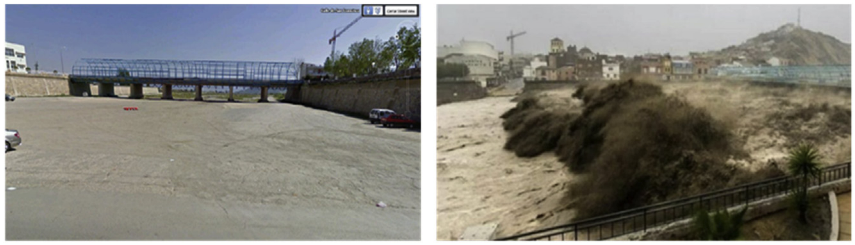

Fig. 3. The increasing flow rate (m^3/s) in the 2012 St. Wenceslas Flood (28/09/2012): 7,24 m^3/s at 12:05, 949,22 m^3/s at 12:10, 1.750,35 m^3/s at 12:15, 255,230 m^3/s at 12:20.

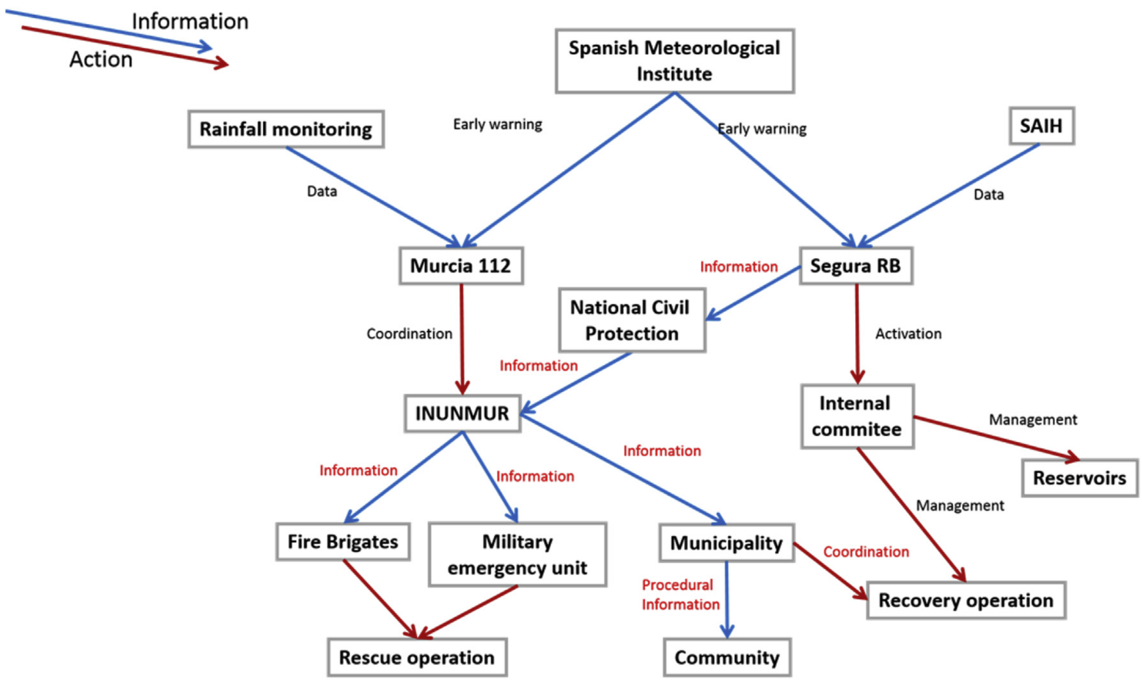

Fig. 4. Protocol of interactions and information flow among the institutional actors in case of emergency.

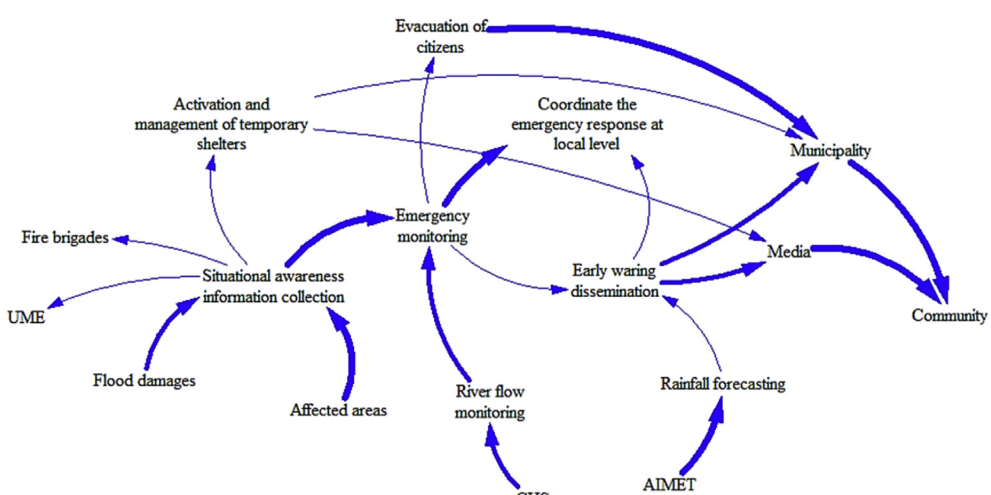

Fig. 5. FCM describing the Murcia emergency management perspective of the network of interaction taking place during an emergency. The thickness of the links represents the different importance degree assigned by the interviewee to the connection.

Table 6
List of institutional stakeholders involved in the flood emergency management.

Name	Role	Acronym
Spanish meteorological Agency	National technical support	N.WF
Segura river basin authority	Regional technical support	L.TS
Murcia emergency management	Local emergency management	L.EM1
Fire brigades	Local operational team	L.OP1
Military emergency unit	National operational team	N.OP
National civil protection	National EM	N.EM
National Government	National coordination	N.GOV
Municipality	Local emergency management	L.EM2
Media	Information provider	MC
Other Municipalities	Local emergency managers	L.EM3
Local Police	Road functionality	L.OP2
Network managers	Road functionality	R.OP2
State police	National emergency unit	N.OP3

According to the protocol of interaction, the Murcia 112 plays the central role in the emergency management. It coordinates the rescue activities of the first responders through the INUNMUR committee. On the other side of the interaction network, the Segura river basin authority, in case of warning, activates its internal monitoring and decision-making committee whose main scope is to adopt the needed actions for managing the water in the reservoir according to the flow of water in the riverbeds.

The Municipality represents the interface between the emergency management authority and the local community. According to the existing protocol of interventions, its main role is to facilitate the flow of information toward the community and to implement the decisions taken by the Murcia 112 at local level, e.g. the evacuation of the local population.

Previous experiences showed some bottlenecks in the "formal" channels of information and data sharing. In particular, the capability of the institutions to provide the community with accessible and understandable information on flood risk was strongly questioned and leaded to some conflicts involving community and institutions. Moreover, ineffective communication among institutional agents – i.e. between the Segura river basin authority and the Murcia 112, and between the Murcia 112 and the Municipality – was registered. Based on these experiences, negotiations were started in order to revise the operative protocol.

This work aims at supporting this revision and adaptation process through the analysis of the formal and informal networks of interaction, and the detection of the vulnerable elements in the network. To this aim, the methodology described in the previous section was implemented.

4. Results

4.1. The elicitation and structuring of the experts' knowledge

The official protocol of interactions to be activated among the institutions in case of emergency was used in this work as a starting point for the definition of the set of actors to be involved in the knowledge elicitation phase. Table 6 shows the list of the institutional actors involved in the cognitive mapping interviews. A main role was associated with the institutional actors as well, which can also be useful to generalize the methodology. The acronyms were selected in order to facilitate the development of the network maps, as shown in the following.

The framework for the FCM development was implemented during individual semi-structured interviews involving the institutional agents. Therefore, participants were firstly required to describe their role in the emergency management and the tasks carried out. Secondly, they were required to describe the information used to support their activities and the actors providing this information. Fig. 6 shows the FCM developed for the Murcia emergency management (L.EM1).

The FCM demonstrated that the main interactions among actors concerned the exchange of information (incoming and/or outcoming) and the cooperation in performing specific tasks in order to achieve the main objectives. An important phase of the knowledge elicitation process concerned the definition of the weights for the links. Different fuzzy linguistic variables were used according to the kind of interaction, i.e. *actor-information*, *information-task*, *task-objective*. Trapezoidal fuzzy functions were used to describe the importance degree, since these were more suitable to describe the participants' judgements (Page et al., 2012). In order to assign the value to the fuzzy variables, participants were asked to identify the most suitable linguistic label to be used and to assess to what extent they were certain about that label. Fig. 6 shows the fuzzy weight for the connection *information-task* in the Murcia emergency management FCM.

Similarly, the FCM for the other institutional actors were developed. As expected, the degree of FCM complexity (Eden, 2004) reflected the actors' role. The more involved in the coordination of the response activities, and the more complex the FCM. This was mainly due to a cognitive bias, i.e. institutional actors tended to mix up their own personal experience (which was the focus of the knowledge elicitation phase) with the protocol of intervention. The aggregation of different individual inputs and the collection of community's experience allowed us to limit the impacts of this bias on the final results.

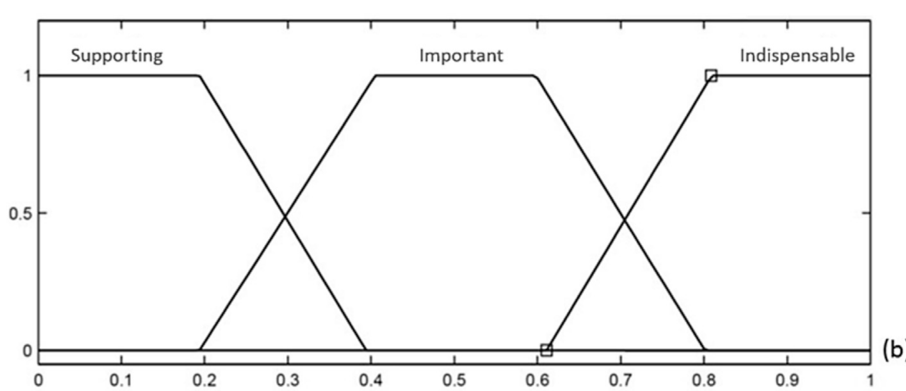

Fig. 6. Fuzzy weight for the connection "river flow monitoring"/"emergency monitoring". The interviewee considered the "river flow monitoring" as "crucial" for implementing the task "emergency monitoring".

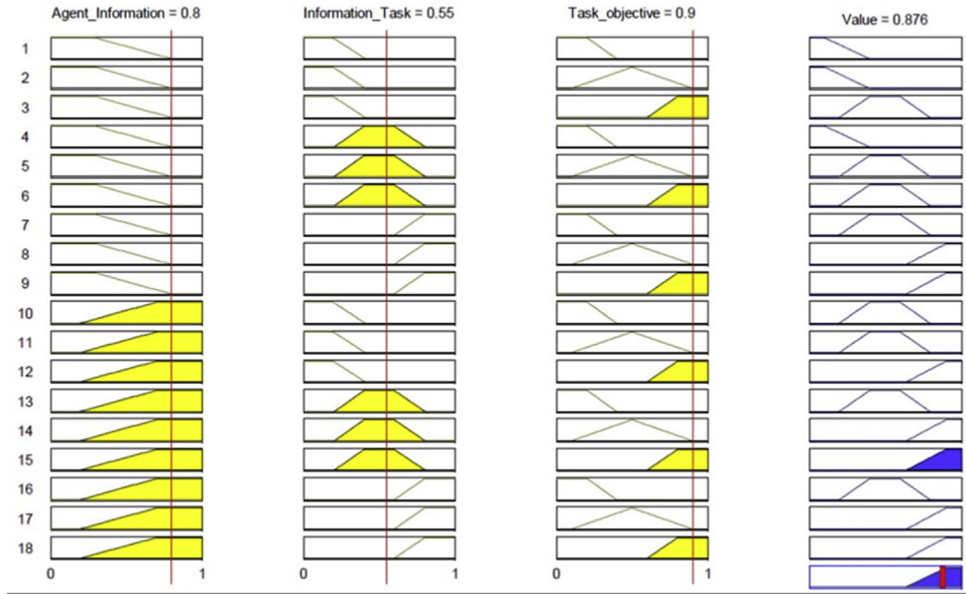

Fig. 7. Result of the aggregation of the fuzzy rules and of the defuzzification process. The yellow parts in the graphs represent the degree of truth of each of the antecedents in the fuzzy rules. The blue parts represent the degree of truth of the consequent of the fuzzy rules (Giordano and Liersch, 2012b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A validation phase was carried out involving the participants. Given the complexity of the developed FCMs, we preferred to validate the individual maps with each participant, rather than validating in a group session an aggregated and even more complex FCM.

Once validated, the FCMs were used to develop the matrices for mapping and analysing the network of interactions. That is, the *Agent* × *Agent*, the *Agent* × *Knowledge*, the *Agent* × *Task*, the *Knowledge* × *Knowledge*, the *Knowledge* × *Task* and the *Task* × *Task* matrices were developed. According to the adopted methodology, the *Agent* × *Agent* matrix was developed by combining the individual row vectors. The values for the vector elements were calculated referring to the following fuzzy *if … then* rule:

> IF the *actor* has **exclusive** access to *information* AND the *information* is **important** for performing the *task* AND the *task* is **important** to achieve the *objective* THEN the value is **high**

In order to obtain the value for the j-th element in the i-th *Agent* × *Agent* row vector, the defuzzification process was performed. The output is a single number calculated as the centroid of the area obtained at the end of the aggregation phase of the fuzzy rules. Fig. 7 shows the results of the inference mechanism for the interaction between Segura river basin authority and the Murcia emergency management.

The final value was 0.876 and represented the importance degree of the interaction involving Murcia emergency management (L.EM1) and Segura river basin authority (L.TS), as perceived by the former actor. The *Agent* × *Agent* row vector for this agent was calculated implementing the same process for the other interaction mentioned in the Murcia emergency management FCM. Table 7 shows the *Agent* × *Agent* matrix, obtained through the aggregation of the single row vectors.

The institutional responders considered the community merely as a passive actor, whose main role was simply to receive the information provided through the official information channels. Institutional actors were not aware of interactions starting from the community – e.g. information provided by the community, or community cooperating with institutional actors in performing some tasks. Therefore, the community's row vector was perceived

Table 7
Agent × *Agent* matrix according to the institutional actors.

	N.WF	L.TS	L.EM1	L.OP1	N.OP	N.EM	N.GOV	L.EM2	MC	C	L.EM3	L.OP2	R.OP2	N.OP3	SPI
N.WF	0	8.3	8.6	0	0	3.7	8.4	0	2	0	0	0	0	0	0
L.TS	10	0	10	0	0	10	0	2.5	2.6	3.2	0	0	4	0	6.7
L.EM1	6	8.7	0	8.3	8.3	4.7	0	4.8	8	8.5	0	0	6.5	6	6.8
L.OP1	0	0	6.3	0	2	0	0	0	0	7.3	0	0	0	0	0
N.OP	0	0	6.6	2.3	0	0	0	0	0	0	0	0	0	0	0
N.EM	3	2.5	4.2	0	0	0	0	0	6.1	0	0	0	8	5.4	6.3
N.GOV	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
L.EM2	0	2	0	1.5	1.3	0	5.7	0	6.3	9.7	8.5	8	0	0	0
MC	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L.EM3	0	0	0	0	0	0	0	8.4	0	0	0	0	0	0	0
L.OP2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R.OP2	0	4.2	6.5	0	0	8.3	0	0	0	0	0	0	0	0	0
N.OP3	0	0	0	0	0	6.4	0	0	0	0	0	0	0	0	0
SPI	0	0	6.7	0	0	6.4	0	0	0	0	0	0	0	0	0

as empty by the institutional actors.

The individual *Agent* × *Knowledge* matrices were developed starting from the individual FCM. The overall matrix was obtained by summing the individual matrices. Similarly, the remaining matrices were developed by aggregating the individual inputs.

4.2. Local community's knowledge elicitation and structuring

A participatory modelling workshop was organized in Lorca involving members of the local community. Specifically, the leaders of the different neighborhoods located around Lorca urban center (*Associacion de vecinos*) were invited to attend the meeting. The neighborhoods to be involved in this phase were selected among the most significantly impacted areas during the last flood episode. The leaders of these small rural communities are not officially elected as representative of the community itself. They are rather considered as leaders because of their wide network of connections within the communities. Therefore, we assumed that their judgement could be considered as a satisfactory approximation of the community's understanding of the network of interactions during a flood emergency episode.

The method described in section 2.2 was implemented in order to elicit local knowledge in a structured way.

Following the framework previously described, the first round concerned the actor-information connection. Participants were required to specify with whom they interacted during the 2012 St. Wenceslas flood, both institutional and non-institutional actors, what information was collected and how this information was used in order to cope with the flood emergency. In order to facilitate the knowledge elicitation process, participants were provided with icons representing the different actors involved in the emergency management.

The weight to be assigned to the links *actors-information* was defined considering the number of participants that acknowledged to have had a particular information through a specific actor. The other weights, i.e. *information-tasks* and *tasks-objective*, were defined involving the participants in a debate (see Fig. 8).

At the end of this phase, the community's FCM was developed (Fig. 9).

The figure shows the role played by the informal network involving the other members of the community. According to the results of the participatory exercise, the cooperation and interaction within the community was fundamental during the last flood episode for both gathering actionable information to reduce the level of risk - i.e. evacuation procedures, evolution of the crisis – and for implementing actions at local level. Specifically, we learned that the leaders of the community were at the center of this informal interaction network. Moreover, they perceived themselves as active responders, capable of cooperating with the official responders (i.e. Military emergency unit and fire brigades) in rescuing affected people and building temporary protections.

The interaction with the main institutional actors involved in

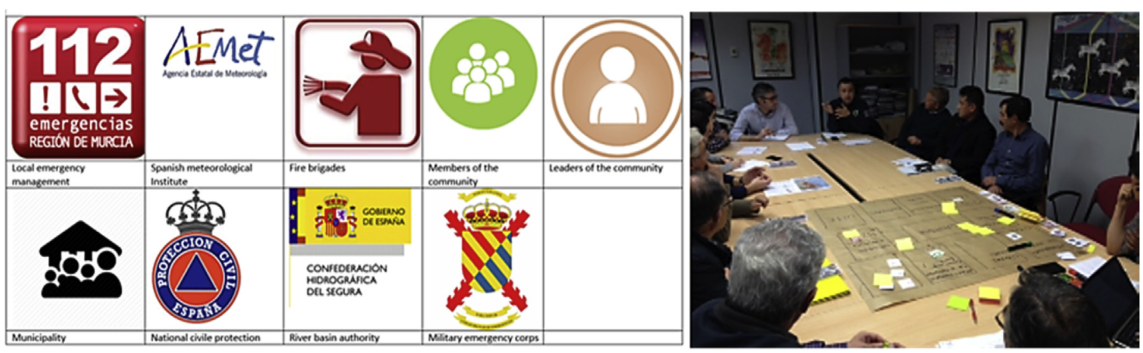

Fig. 8. Participatory modelling exercise.

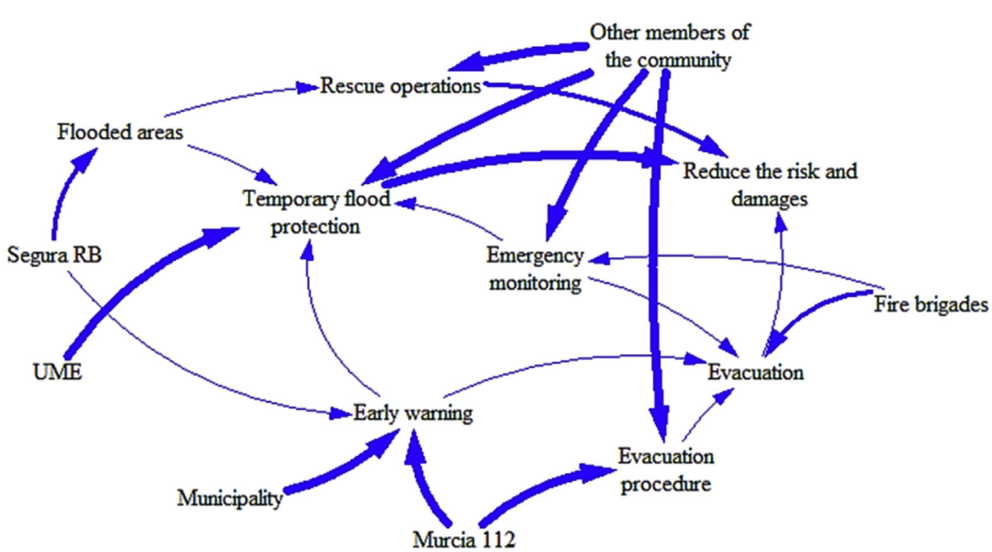

Fig. 9. Community's FCM.

the emergency management was not considered satisfactory. Specifically, the information provided by the municipality and the Murcia emergency management was not considered important for the implementation of the main actions (low importance degree). This was mainly due to the limited understandability of the institutional information.

The obtained FCM was used to develop the community's row vector describing the interactions between the community and the other actors from the community point of view. The set of actors was increased in order to account for the role of the community leaders.

4.3. Mapping and analyzing the network of interaction

The model of the complex network of interactions for the case study was developed using the aggregated matrices as basis. Specifically, the *Agent* × *Agent* network was developed by combining the community's row vector with the institutional matrix (Table 7). Similarly, the other networks were obtained by summing the community's and the institutional matrices. The matrices were used as input for the development of the networks maps. The software ORA© was used to this aim. Fig. 10 shows the Social Network, that is, the map of the *Agent* × *Agent* interaction.

The direction of the links indicate which agent mentioned the interaction. For instance, the link between L.EM2 and L.OP2 shows that L.EM2 perceived itself interacting with L.OP2, but not vice-versa. The thickness of the links represent the weights assigned by the different actors during the knowledge elicitation phase. The comparison between this network and the one representing the official protocol of interactions in case of emergency (see Fig. 5) demonstrates the inadequacy of the protocols to fully describe the complexity of the interactions. The actual network is far less hierarchical and accounts for informal interactions taking place even among institutional actors. That is, during the knowledge elicitation phase we learned that, besides the official interactions, in case of emergency the institutional actors activated personal relationships to gather important information.

Fig. 11 shows the *Agent* × *Knowledge* network. Table 8 shows the set of information used during the emergency, according to the institutional agents and the community leaders.

The map demonstrates that there is no exclusivity in the *agent-*

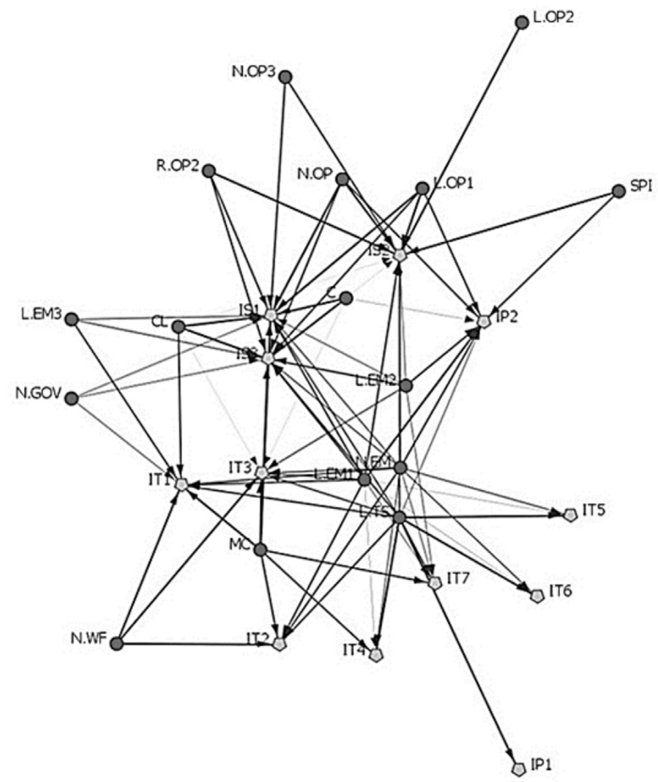

Fig. 11. Map of the *Agent* × *Knowledge* network.

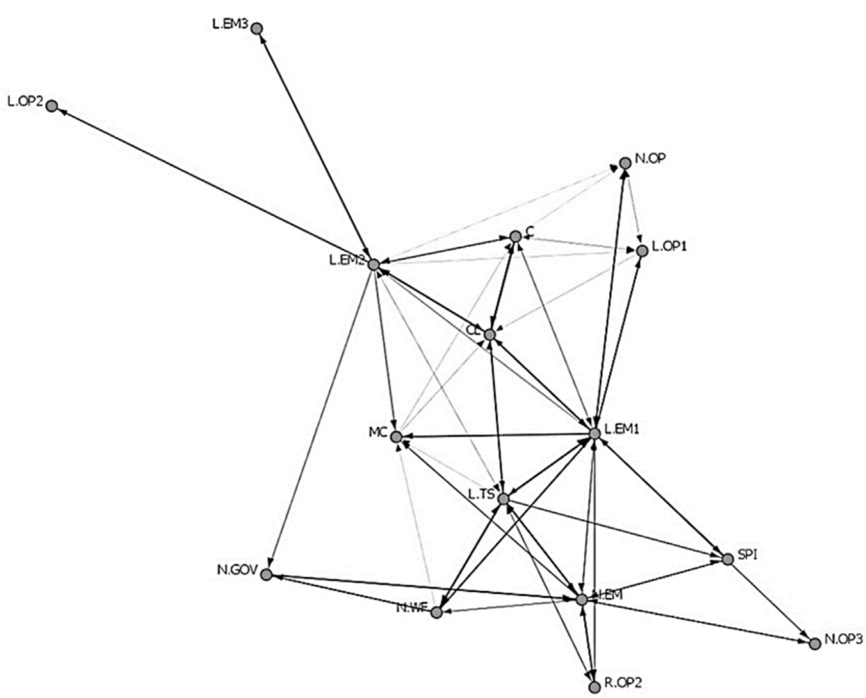

Fig. 10. Map of the *Agent* × *Agent* interactions taking place during the flash flood emergency management in Lorca.

Table 8
List of information used by each agent when implementing their tasks.

Information	Acronym
Rainfall monitoring	IT1
Rainfall forecasting	IT2
Early warning	IT3
River-flow monitoring	IT4
River-flow forecasting	IT5
Stock-water forecasting	IT6
Reservoir emergency management plan	IP1
Flood emergency management plan	IP2
Emergency management plan	IP3
Flooded areas	IS1
State of the infrastructures	IS2
Flood damages	IS3

knowledge interactions, namely there is no actor exclusively owning pieces of knowledge. Therefore, the cooperation among the different actors is relavant to overcome the fractured nature of the information system.

The combination of the different networks allowed to map the complex interactions among the main elements activated during the flood emergency, i.e. agents, knowledge and tasks (Fig. 12).

Fig. 12 shows the actual complexity of the interaction mechanisms supporting the emergency management. Failure in this network – i.e. lack of an information, missing cooperation for task implementation, etc. – could provoke uncontrollable cascading effects leading to failure of the whole emergency management process. Therefore, it becomes crucial for the emergency managers to enhance their comprehension of this complexity, in order to implement actions aiming to increase the effectiveness of the emergency management network and to reduce its vulnerability.

To this aim, the graph theory measures described in section 3.4 were implemented in order to identify the key elements and the main vulnerabilities of the network. Table 9 shows the results of the analysis aiming at identifying the key agents in the network.

The analysis allowed us to identify the most crucial agents in the network accounting for the complexity of their relationships with the other agents, which affects their capability in moving information from one side of the network to the other. Moreover, the adopted approach assumed that an agent is crucial in the network performance if she/he brings important knowledge and if she/he cooperates in performing important tasks.

The results of analysis demonstrate the importance of the three most influential institutional actors at local level, i.e. the Segura river basin authority, the Murcia emergency management and the municipality. These actors had a dense network of interactions with the other agents (centrality measures), and had access to a wide set of relevant information allowing them to carry out tasks. Beside these results, the analysis of the network emphasizes the actual role in the emergency management of the community leaders and the media. These actors were not mentioned in the official protocol of intervention. Specifically, the community leaders could easily act as an interface between the institutional system and the local communities. Their high value of the betweennes centrality and hub centrality demonstrate that these actors could facilitate the sharing of the emergency information.

Similarly, the analysis of the network showed that the media plays a role during an emergency. Most of the institutional actors had direct contact with media. Therefore, they have access to important information – i.e, most knowledge measure.

The developed network was also analysed in order to identify key vulnerabilities, i.e. those elements that could lead to failures of the emergency management operations and/or to decreasing effectiveness of the responding actions. The graph measures mentioned in Table 5 were implemented. The key vulnerabilities are described in the Table 10.

5. Discussion

This section means to critically reflect upon the experiences

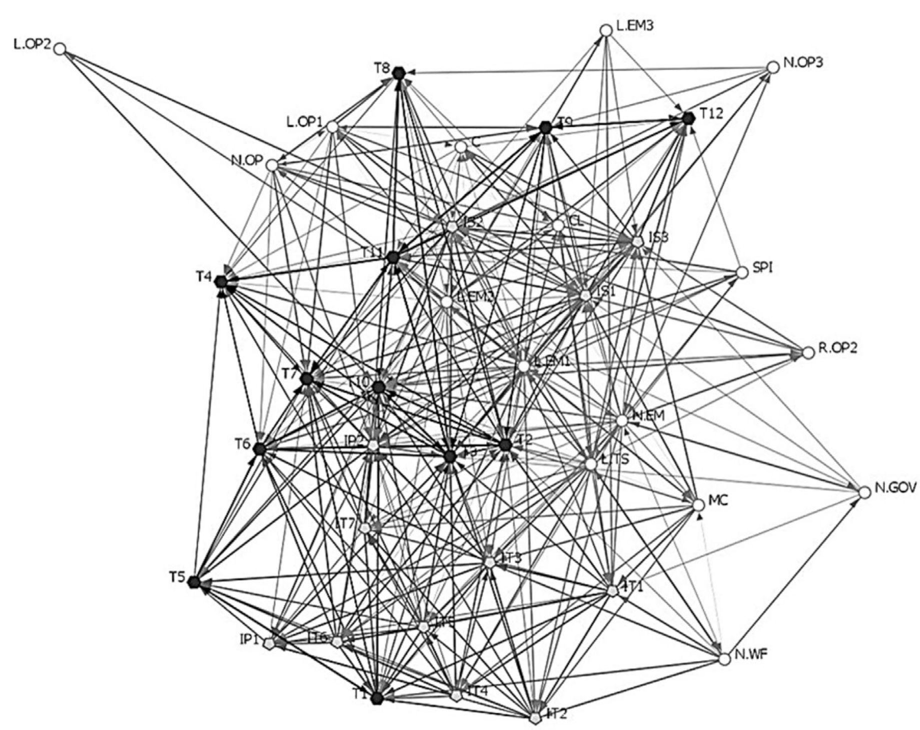

Fig. 12. Network of interaction among Agents, Knowledge and Task according to both experts and local knowledge.

Table 9
Key agents in the Lorca flood emergency network.

Measures	Key actor	Meaning
Total centrality degree	National civil protection Municipality	These actors are characterized by a high number of connection (both in- and out-) with most of the other agents in the network.
Betweennes Centrality	Municipality Segura RBA Murcia 112 Community leaders	These actors occur on many of the shortest paths between other agents. This means that these actors can easily move information from one part of the other of the network.
Hub centrality	Segura RBA Murcia 112 Community leaders	Individuals or organizations that act as hubs are sending information to a wide range of others each of whom has many others reporting to them. Therefore, they act as hub of information within the network.
Most knowledge	Segura RBA Murcia 112 National civil protection Media	These actors have access to important pieces of information.
Most task	Murcia 112 Municipality National civil protection Segura RBA	These actors are called to perform the most important tasks.

carried out in the case study and to answer to the main research question of this work, that is: is the integration between PSM approach and quantitative SNA capable to support emergency managers in understanding the complexity of the network of interactions (macro-level), accounting for the individuals' behaviour (micro-level)?

To this aim, firstly, this section analyses the capability of the integrated methodology in facilitating the integration between qualitative and quantitative analysis of the network of interactions taking place during an emergency. Secondly, this section discusses the usability of the quantitative SNA measures to enhance the comprehension of the actual roles and responsibilities in emergency management and, in doing so, to support the creation of an effective collaborative emergency management environment.

Concerning the first issue, this work is in line with several scholars' approaches based on the integration between qualitative and quantitative analysis of the social network (see for example Schipper and Spekkink, 2015). To this aim, this work used the individual experiences as basis for mapping the network of interactions during the emergency management. The PSM, and specifically the FCM approach, proved to be a useful tool for eliciting the individual narratives about the emergency management, and to structure them for the quantitative analysis of the interactions network. The causal structure of the FCMs was defined to account for the motivation and purposes of the interactions (i.e. information sharing, cooperative task performance, resources sharing), and not only for the form of the relations (i.e. strengths of the links), such as in most of the quantitative SNA. The FCM translate this qualitative information into fuzzy numbers to be used as inputs for the meta-networks, and for the quantitative analysis of the social network. Therefore, the experiences carried out in the case study showed several benefits related to the integration between storytelling approaches and PSM for mapping and analysing the emergency interactions. Firstly, the individual narratives allowed us to overcome the limits imposed to the lack of quantitative data concerning the informal interactions activated in case of emergency. Secondly, the FCM capabilities to translate qualitative data into fuzzy numbers contributed to the development of the SNA meta-matrixes without increasing the stakeholders' fatigue. Linguistic assessment were used instead of quantitative data. Finally, the results demonstrated the suitability of the adopted modelling approach in addressing the knowledge-action gaps issues. The SNA allowed to investigate the network structure at the basis of the emergency management decision-making process, contributing to identify all the stakeholders that need to be involved in the knowledge co-creation process (Muñoz-Erickson, 2014; Muñoz-Erickson and Cutts, 2016). Moreover, the involvement of the local stakeholders since the initial phases of the analysis, and the

Table 10
Key vulnerability in the network of Lorca flood emergency management.

Type of elements	Key vulnerability	Meaning
Agent	Community leaders	This actor has a high degree of centrality but low degree of most knowledge. Therefore, she/he has access to limited knowledge impeding their role as information providers. They represents a barrier to information sharing rather than a bridge.
	Municipality	This actor has a high degree of most task and a low degree of most knowledge. This is mainly due to the limited capacity of the municipality to understand the technical information provided by the other actors. As result, the effectiveness of its action is limited.
	Media	This actor has a high degree of most knowledge, because it receives information directly from the institutional actors. Nevertheless, its low centrality degree reduces its capability to effectively share the information with the community.
Knowledge	Flood emergency management plan	This information should play a crucial role since it has a high most task degree (it supports a large number of tasks). Nevertheless, it is poorly shared among the different agents (low degree of most knowledge).
	River flow monitoring and forecasting	This information represents a key vulnerability because it has a high betweennes centrality in the *knowledge* $\times$ *knowledge* network (i.e. it could activate other information), but it has a very low degree of most agent. Therefore, it is not easily accessible.
Task	Preparedness activity with community	This task is characterized by a high centrality degree in the *Task* $\times$ *Task* network. That is, it could facilitate the implementation of numerous other tasks. Nevertheless, only the municipality is responsible for the correct implementation of this task.

integration of their own narratives in the model of the network developed a sense of ownership toward the obtained model and the results of the analysis. The integration of stakeholders knowledge into the modelling process was meant to fill the gaps between the knowledge producers (i.e. the analysts), and the knowledge users (i.e. the emergency managers) (Weichselgartner and Kasperson, 2010). In doing so, we recognized that emergency management is among those cases in which reliable scientific knowledge is no longer enough. The collection and integration of individual narratives, the structuring of these different viewpoints into FCM, constitutes an attempt to enable a shift toward a socially-robust knowledge for improving the coordination in a multi-agency emergency management process (Muñoz-Erickson, 2014; Weichselgartner and Kasperson, 2010).

The results of this participatory network modelling phase were used to structure the debate involving institutional actors and the community leaders. The debate aimed at co-developing potential strategies to improve the emergency protocol. Moreover, the network modelling approaches was used to assess the actual impacts of suggested changes on the network effectiveness. In the first phase, participants discussed the meaning of the measures describing the key vulnerability in the emergency network. The analysis carried out in this work increased their awareness about the role played by the informal interactions taking place within the institutional system and between institutional actors and the members of the community. The discussion initially focused on the role of the media. Most of the institutional actors agreed that enabling a more effective bi-directional communication with the community members through the social media would be beneficial for sharing emergency information. The institutional actors were interested in enhancing the capability of the current media channels to collect, store and analyse the feedbacks from the community. The capability of local communities to contribute to the monitoring of the emergency evolution was deemed important by the participants. From the network topology point of view, the proposed change provoked an increase of the media centrality degree of the media in the agent × agent network, and, because of the media position in the network and its capabilities to access information, it augmented the speed of the information flow.

Another important change to be introduced in the network of interactions concerned the capability of the community leader to access and comprehend crucial information during emergency. This required enhancing the strength of the links involving community leaders in the agent × knowledge meta-network. Specifically, the links between community leaders and the flood emergency management procedures, and between community leaders and the early warning need to be strengthened. To this aim, the cooperation between institutional actors and the local community was considered crucial. Suggestions were made to train the community leaders allowing them to better comprehend technical information. According to the results of the discussion, this activity could improve the capability of local population to react in case of emergency in cooperation with the official responders. The introduction of these changes in the SNA caused an increase of the "most agent" measure of the two above mentioned information. Moreover, the "most knowledge" degree of the community leaders increased.

Therefore, the first and most important positive result of the implemented methodology concerns the increased awareness of the institutional actors about the need to shift the focus from investing economic and human resources in developing innovative emergency information collection tools, toward enhancing the capability of the different actors to cooperate in case of emergency.

Moreover, the obtained results demonstrated that the methodology was capable of accounting for the differences in organizational culture and to analyse how those differences could lead to different management of emergency information. As demonstrated by different scholars (e.g. (Maitlis, 2005; Smart and Sycara, 2013; Wolbers and Boersma, 2013), differences in organizational culture affect the sense-making process, that is, the way different responders search for information, select information and give an interpretation to the collected information. The results described in this work contribute to demonstrate how organizational culture influence the strategy adopted by each responders for collecting useful information. To this aim, the network size measure was implemented, as shown in the Table 11.

The Effective Network Size measure is calculated accounting for the number of ties linking a node to the others. That is, the higher is this value for the agent A, the wider is her/his ego-network.

As shown in the table, some institutional actors – e.g. the Murcia emergency management – had a dense network of interactions, and considered the multi-central structure as the most effective structure for the rapid exchange of information within each level of the organizational structure and between different levels. Due to the size of their interaction network with the others, this actor seemed capable of adapting its information collection strategy to the different conditions, showing resilience to failures of the official protocols of information sharing. Institutional actors with a dense network of interactions seemed to be capable of shifting from the formal to the informal network in order to gather the needed information. On the other hand, the official responders – e.g. the UME and the fire brigades – assumed a strongly hierarchical structure of the information exchange process. These actors trusted exclusively information flowing from the vertex through intermediary, and easily recognizable, levels. This is because they needed to reduce the "noise" in information collection. Neglecting these differences could lead to the development of ineffective strategies for information sharing for emergency management. Integrating the Murcia emergency management in a hierarchically structured network could negatively affect its role as response coordinator. Contrarily, increasing the number of information centres in the responders' networks could lead to the paralysis of their activities. The experiences carried out in Lorca suggested that developing effective emergency management strategies requires a clear understating of the differences among agents' understanding of the interaction network.

Finally, the experienced carried out in Lorca case study confirmed the dynamic nature of the interaction network for the emergency management, as described by different authors (e.g. Naim Kapucu and Demiroz, 2017; Noori et al., 2016). The quantitative analysis of the dynamic evolution of the temporary responding multi-organization, and the changes of roles and responsibilities of the different organizations, is beyond the scope of this work. Nevertheless, the collected narratives allowed us to draw some interesting, although preliminary, conclusions. The analysis demonstrated that the main changes were related to the activation

Table 11
The effective size of a node's ego network.

Actor	Effective Network Size
Murcia emergency management	10.22
Municipality	8.70
National Civile Protection	6.25
Segura river basin authority	5.45
Media	4.64
Community leaders	4.18
Spanish meteorological Institute	3.82
Fire brigades	2.72
Military emergency unit (UME)	1.56

of informal interactions, involving the three main responders at local level, i.e. the Murcia 112, the Segura River Basin authority (CHS) and the local community. In the early stage of the emergency management, the institutional actors operated according to the official protocol (Fig. 4). Therefore, no direct interaction was registered between the CHS and the Murcia 112. In this phase, CHS activated an internal committee for assuring the correct management of the reservoirs, and interact with the AEMET and the national civil protection. No other responders had access to information related to the reservoirs management. In this phase, the CHS played the central role, because of its capability to manage this crucial information. Therefore, the CHS had the highest raking in the “Most knowledge” measure.

When the emergency became more problematic, the Murcia 112 activated informal, pre-existing on personal basis, connections with the CHS in order to obtain this information and to use it in the emergency management. Contemporarily, the community members diverted their attention from the information provided by the municipality, toward the interaction with the community leaders – considered as capable of providing suggestions to reduce the risks – and the Murcia 112. This evolution of the interaction network provoked changes in the role played by the different agents. That is, the Murcia 112 became the central actor because of its centrality in the interaction network and the access to crucial information. The community leaders emerged as key actors because of their capability to operate as informal emergency responders, and to provide trustable information to the community members.

The quantitative analysis of the dynamic evolution of the topology of the interaction networks, and its impacts on the network measures will discussed as a further development of this work.

6. Concluding remarks

This work demonstrates that effective cooperation for emergency management requires a shift from simply improving information management technologies toward enhancing the interaction processes among the actors involved in emergency management. This work demonstrates that one of the main barriers hampering this enhancement is the limited comprehension of the interaction mechanisms during an emergency. Conceiving interaction exclusively as an information sharing process represents only part of the truth. Institutional and non-institutional emergency responders interact each other in different ways, ranging from the co-creation of knowledge to the co-implementation of tasks. The development of an effective emergency management plan aiming at supporting the collaborative emergency response claims for tools and methods capable to unravel the complexity of the network of interactions. As demonstrated in this work, the knowledge obtained through the analysis of the network could be used to make the different actors aware of role, responsibilities and resources that the other brings in the interaction network in case of emergency, informing a debate leading to the development of a more effective protocols of interventions, capable to account for both the formal and informal interaction networks.

The paper details the design and implementation of an integrated approach whose main scope was to gather the complexity of the interactions through the community's and experts' narratives, and structuring these narratives in order to implement SNA aiming at unravelling the complexity. Specifically, the narratives collected through the SA phase supported the interpretation of the graphs developed using the SNA. FCM acted as an interface between these two methods by transforming the narratives into inputs for the SNA. The integrated approach leads to the understanding of the emergency interaction network in order to make clear the role played by each actor in the network, enabling the collective decision-making process for the management of emergency interaction network.

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