sustainability

MDPI

Article

Promoting Disaster Resilience: Operation Mechanisms and Self-Organizing Processes of Crowdsourcing

Zhijun Song [1], Hui Zhang [1,2,*] and Chris Dolan [3]

[1] School of Public Administration, Guangzhou University, Guangzhou 510006, China; songzongzijun@gmail.com
[2] Institute for Risk & Disaster Reduction, University College London, London WC1E 6BT, UK
[3] Institute of Advanced Studies, University College London, London WC1E 6BT, UK; Chris.Dolan@cantab.net
* Correspondence: zhangh3377@gmail.com or hui.zhang@ucl.ac.uk; Tel.:+86-13560065730

Received: 25 December 2019; Accepted: 25 February 2020; Published: 1 March 2020

Abstract: It is often difficult to realize effective governance and management within the inherent complexity and uncertainty of disasters. The application of crowdsourcing, through encouraging voluntary support from the general public, advances efficient disaster governance. Twelve international case studies of crowdsourcing and natural disaster governance were collected for in-depth analysis. Influenced by Complex Adaptive System theory, we explored the self-organizing operation mechanisms and self-organization processes of crowdsourcing within disaster governance. The self-organizing operation mechanisms of crowdsourcing are influenced by the multi-directional interaction between the crowdsourcing platform, the initiator (who commences the crowdsourcing process) and the contractor (who undertakes disaster reduction tasks). The benefits of crowdsourcing for governance structure and self-organization processes in natural disaster governance are reflected in three perspectives: strengthening communication and coordination, optimizing emergency decision-making, and improving the ability to learn and adapt. This paper discusses how crowdsourcing can promote disaster resilience from the perspective of the complex adaptive system to enrich the theoretical research on crowdsourcing and disaster resilience.

Keywords: Social media; Complex adaptive system; Self-organization; Public participation; Co-creation; Co-design; Crowdsourcing

1. Introduction

During a disaster, the search, communication, and feedback process for information determines the various agents' actions [1], which helps drive self-organization. Self-organization is the collective process where various agents communicate, choose and adjust each other's behaviors in order to enable the achievement of common goals [1]. In the process of realizing a common goal for disaster reduction, participants will adjust their self-organizing behaviors in relation to the changing disaster environment.

Given the considerable and unpredictable social and economic impact of disasters, ensuring the disaster system is self-organizing is instrumental to effective disaster governance. Crowdsourcing is the voluntary online engagement of heterogeneous groups, individuals, institutions, non-profit organizations, and companies who bring different knowledge and skills to disaster response [2]. Previous studies have explored the construction of disaster resilience from the perspective of community engagement. For example, Wells et al. (2013) constructed a framework of community engagement in disaster response [3]. In this framework, community engagement promotes equal decision-making through two-way knowledge exchange among stakeholders, and combined with policy support, can promote the development of community networks and the integration with public forces, thus

enhancing community resilience. The research conducted by Baybay and Hindmarsh (2018) in coastal communities in the Philippines shows that community engagement can be increased by improving community activities, knowledge, skills, resources, and by adopting local culture and customs, which are crucial to promoting community resilience [4]. Traditional community engagement refers to offline action processes, while the Internet provides a new form of online community engagement. Crowdsourcing platforms, such as portals, social media, and online applications, have become effective tools for community engagement, by reducing the transaction costs associated with information search, analysis, and decision-making, as well as lowering resource costs (time, money, health, etc.) for civic engagement [5]. Crowdsourcing expands the boundaries of traditional community engagement, which is not limited by time or space, while people from all over the world can participate in specific actions online anytime and anywhere.

The issue of how crowdsourcing promotes the self-organization process and builds disaster resilience is understudied. Existing research focuses on how crowdsourcing can be used to collect and analyze disaster data, as well as crowdsourcing's use in communication, loss assessment, and decision support. Research focuses on the functions of crowdsourcing at the technical level, but does not consider the interaction between different subjects in crowdsourcing from the perspective of disaster governance. Taking a tactical emphasis, many studies are based on a single case that focuses on how crowdsourcing can mitigate local problems caused by a specific disaster [6–8]. This paper analyses 12 worldwide crowdsourcing cases, to explore the overall strategic application of crowdsourcing for improved disaster resilience. Utilizing the Complex Adaptive System theory, we analyze the self-organizing operation mechanisms and self-organizing processes of crowdsourcing in disaster governance, and discuss how crowdsourcing can promote disaster resilience.

2. Literature Review

2.1. The Application of Crowdsourcing in Disaster Governance

Jeff Howe first proposed the term 'crowdsourcing' and defines it as a business, organization, or individual that outsources work that is traditionally performed by a designated agent (usually an employee) to a (non-specific) public to undertake in a voluntary capacity [9]. Crowdsourcing, as an internet-based public participation model, immediately attracted extensive attention from both business and academics.

Crowdsourcing research on disaster governance often focuses on the collection and analysis of disaster data. For example, Degrossi (2014) proposed a crowdsourcing-based approach, the Flood Citizen Observatory, to obtain information from volunteers in flood-prone areas to improve Brazilian flood risk management [10]. Similarly, Chu et al. (2012) developed a system, named CROSS (a crowdsourcing support system) for disaster monitoring, which collects information reported by volunteers that is used to build a comprehensive understanding of threatened areas before and during disasters [11]. Most crowdsourced information is unstructured and unorganized and needs to be collated and analyzed before it can be used. Ortmann et al. (2011) studied how to classify disaster information using 'linked open data', which means recording disaster-reduction information in a standardized way (as Resource Description Framework triples—subject, predicate, object) to enable data to be more easily shared and interconnected [12]. Schulz et al. (2012) demonstrated a machine learning approach that aims to transform large amounts of unstructured crowdsourced information into usable information to support 'command staff' (which we call initiators in this paper) to make more informed decisions [13]. The focus of these research is on the technical ways that crowdsourcing can be used for disaster data collection and analysis. The strategic nature of disaster governance and the role of the public in the crowdsourcing process has not been considered.

Crowdsourcing has four characteristics: openness, dynamics, autonomy, and extensiveness: (1) Openness. The public can use open source methods and media to participate. (2) Dynamics. The depth and breadth of public participation can change dynamically. (3) Autonomy. The public has

no specific employer restrictions and can participate independently. (4) Extensiveness. Through network aggregation, participants are widely distributed geographically. These characteristics fit well with the need for disaster governance to widely mobilize public participation and make effective use of collective intelligence. Crowdsourcing enables better communication and coordination between disaster victims, spontaneous volunteers, and official relief agencies [14,15], because it enables timely data for loss assessment [16] and identification of disaster problems [14,17] for enhanced rescue implementation [18]. For example, Sahana [19] is a crowdsourcing system that was built to help manage the 2004 Indian ocean tsunami. Sahana is designed to help manage the coordination and collaboration problems caused by disasters—it supports the search for missing persons, coordination of relief work, and facilitates the reporting about disasters in a timely manner [20]. Similar studies have explored how crowdsourcing facilitates better communication and collaboration through specifically designed crowdsourcing platforms like 'City-share' for disaster coordination [21] and 'Outbreak Near Me' which was used to raise public awareness of the 2009 influenza (H1N1) outbreak [22], as well as mainstream platforms like Twitter [14,23]. Crowdsourcing is also essential for pre-disaster public awareness and preparedness, and the post-disaster recovery stage where disaster-related photos, video, written documents, and social information can be collected, sorted and structured to help identify the severely damaged and vulnerable areas to support reconstruction decisions [15]. These studies play an important role in understanding crowdsourcing mechanisms in the context of disaster governance. However, there is a limited analysis on the overall application of crowdsourcing in the disaster response system and a lack of exploration of the application value of crowdsourcing through the perspective of disaster resilience.

2.2. Disaster Resilience

Disaster resilience research is increasingly central to the field of disaster governance. Most scholars argue that disaster resilience is the process and capability of the human system to deal with disaster events [24]. Disaster resilience includes prevention and early warning capability for disasters [17], rapid response and recovery to disaster events [25], and the ability to learn and adapt to reduce the impact of future disasters [26].

Fundamentally, improving disaster resilience is to build the system's self-organizing ability, and its construction path is closely related to the system's pre-disaster endowment and specific disaster scenarios [27]. This can be approached from a practical engineering perspective (infrastructure and the built environment) or through the social sciences to consider the 'human' and 'institutional' perspective. From the perspective of system theory, to upgrade the function of the system, we need to focus on the structure and hierarchy of the system. If the information links within and between each level in the system are properly designed, feedback delay will be reduced, and information overload will decrease so that the operating efficiency and adaptability of the system will be greatly improved. Most scholars believe that preventing the unequal distribution of information resources before and after disasters, improving the degree of citizen participation in disaster governance [28], cultivating the organizational network and inter-organizational cooperation [29], and establishing an effective information communication network [30] are all crucial to improving self-organizing ability. However, there is a lack of discussion on how to strategically build disaster resilience in different contexts.

2.3. Complex Adaptive System (CAS) Conceptual Framework

CAS theory provides a new perspective to study how crowdsourcing can promote disaster resilience. Manyena (2006) argues that a holistic approach to systems theory can enhance understanding of disaster risk and social vulnerability to help build resilience [31]. Coetzee et al. (2016) proposed that through the application of CAS, disaster resilience and its inherent dynamics can be better understood, which can provide effective tools for disaster risk governance and resilience construction in the future [32]. They proposed five CAS concepts that describe the system, which inform the conceptual framework in this paper [32]: (1) Non-linearity: the inputs into the system may have unexpected

outputs, and a small input might have a large consequence; (2) Aggregation: in complex systems, individuals organize themselves into their own groups, through similar needs, practices and interests; (3) Emergent behavior: large macro system-level characteristics and properties can materialize from the micro-level; (4) Feedback loops and adaptation: feedback loops can improve or detract from the CAS, but because actors learn from past events the system is constantly dynamic; and (5) Context-based responses: the functioning of the system is so heavily affected by context that it makes each CAS unique.

An important element in CAS is the adaptive subject, which can interact with the environment and other subjects, and continuously adapts, learns, accumulates experience, and then changes their own behavior [33]. Comfort (2004) argued that self-organizing behavior based on input information is the driving force for the dynamic development of CAS [34]. Holland (1995) proposed that, in the process of self-organization, the subjects involved can adjust their actions according to the observed or obtained information to adapt to the changes in the environment [33]. Comfort (2004) believes that the interaction between the subjects participating in the disaster response forms a disaster response system (producing self-organizing), revealing a kind of spontaneous sequence (producing self-organizing processes) [34]. The coordination of actions in complex disaster response systems depends on the scope and effectiveness of the information and communication processes in which the systems operate, and the resulting ability to promote collective learning and adaptation [1]. When the intelligence-gathering function is weakened, the ability of each subject in the system to 'understand' its operating environment will fail [35]. Without this ability, the actors cannot integrate relevant new information into their previous knowledge base. In the absence of information that forms a system-wide perspective, individual subjects make individual decisions that may contradict or conflict with system-wide objectives and disadvantage other subjects within the system. In this case, the relationship between the various subjects in the system becomes fragile and tends to break under the pressure of urgent and sensitive events.

Advances in information technology, like crowdsourcing, provide a way to solve the communication and coordination problems among the various subjects in the system. Crowdsourcing provides greater capabilities to store, exchange, integrate, and synthesize information in a timely manner to support decision-making and improve actions between multiple actors operating in complex environments. This study regards the disaster response system with crowdsourcing intervention as a complex adaptive system, and this paper tries to analyze the subjects, interactions between subjects and self-organizing processes within this system.

3. Method

Using the multi-case study method, this paper adopts an explanatory approach to how crowdsourcing can promote disaster resilience. The case study method was utilized for three reasons. Firstly, the case study method is more suitable for asking 'how' and 'why' questions about a target phenomenon (crowdsourcing and CAS), and it is more suitable for a research field that has little or no attention [36]. Secondly, this paper explores the operation mechanisms and the self-organization processes of crowdsourcing in the context of disasters. Case studies can vividly and carefully analyze the logic and rules of complex phenomena and reveal the hidden motivation behind the phenomenon. Thirdly, case studies have advantages in displaying dynamic evolution processes and can deeply reveal the evolution path of the process [37], allowing an in-depth analysis of the self-organizing process. Furthermore, compared with a single-case study, this multi-case study allows cross-case mode exploration, which can further deep observation of the processes and results in multiple contexts, helping improve the universality of the findings in other contexts. And according to Eisenhardt (1989), a multi-case study approach using at least four cases is more credible and scientific [38]. On 1–10 January 2019, the cases were obtained from the Google and Web of Science databases. The object of retrieval was restricted to 'natural disasters' caused by natural disaster factors. Natural disaster factors are natural processes or phenomena that may cause casualties or health effects, property loss, loss of livelihood and service facilities, social and economic disruption or environmental damage. Man-made

disasters such as terrorist attacks and wars were not included. In order to ensure a comprehensive range of obtained cases, the retrieval strategy was: TS = (Crowdsourcing) AND (Disaster) AND TS = (Disaster* OR Flood* OR Earthquake* OR Tornado* OR Hazard* OR Typhoon* OR Landslide* OR Fire* OR Tsunami * OR Drought OR Cyclone* OR Storm* OR Hail OR Epidemic* OR Plague*). The retrieval period was set between 2006 and 2019 because crowdsourcing was first proposed in 2006. Articles and reviews were prioritized for retrieval and editorial materials, book extracts, book reviews, news and conference summaries, and other forms of literature were excluded. After filtering the search results, cases with limited information or relevance on crowdsourcing and repetitive content were excluded. This selection criterion enabled 12 cases of the application of crowdsourcing in disaster governance (Table 1). A qualitative content analysis method was used to analyze the cases, with emphasis on allowing categories to emerge out of the data and on recognizing the significance of the context in which an item being analyzed (and the categories derived from it) appeared [39]. According to the CAS theory, the analysis is carried out from the aspects of adaptive subjects as basic elements, exploring the interaction between subjects, and self-organizing processes.

Table 1. Brief Description of Crowdsourcing Cases in Disasters.

Number	Event	The Application of Crowdsourcing
1	China 2008 Wenchuan Earthquake [40]	The 'Home of the volunteers' group on QQ (a Chinese commercial instant messaging service), gathered more than 200 active volunteers, who coordinated more than a third of the provincial Sichuan civil organizations to participate in disaster relief operations. The Douban (a social networking site) volunteer team collected disaster information on relief needs from across the internet, using sources such as blogs, local radio station websites, and QQ groups of rescue workers and rescue organizations. The processed information was classified with symbols, to portray the information visually on the crisis map.
2	China 2010 Yushu Earthquake [40]	The Huaxia Commonwealth Service Centre (a coalition of NGOs) set up a special forum on their website to release information about the disaster and to coordinate and organize members, other social groups and individual volunteers to participate in disaster relief. The released information was predominantly collected through two social networks: the Blue Sky Rescue (an alliance of civic outdoor rescue teams), and a network alumni association composed of students and white-collar professionals from the Qinghai Province.
3	Republic of Haiti 2010 Haiti Earthquake [41]	The public sent text messages, emails, Twitter, Facebook, and other social media about stranded people, medical conditions, tents, and food needs to Ushahidi (a crowdsourcing platform for social activism and public accountability). This information was verified, processed and mapped by remote digital volunteers. The Open Street Map (OSM), an open-source mapping project, was used by international digital volunteers to create a more accurate map of Haiti. Finally, victims sent free 'help-wanted' messages to the text hotline Mission4636, which were translated, processed and forwarded to relief organizations by digital volunteers.
4	Japan 2011 East Japan Earthquake [42]	Japanese OSM volunteers closely monitored Twitter to collect, analyze and map crisis-related data to Sinsai.info (a crisis-mapping site that uses the Ushahidi platform). This provided comprehensive and timely information on the scope of the disaster and the resulting relief needs.
5	Nepal 2015 Nepal Earthquake [43]	Nepalese expatriates and local volunteers developed a crowdsourcing platform called kaha.co, which allowed those in need to easily reach out to those who were donating support. The platform allowed people to fill out forms to request help, and the local public and aid organizations to post about donated resources and services that they could provide.
6	USA 2009 Wildfire in Southern California [44]	Volunteers created a crisis map site that synthesizes various online sources such as tweets, MODIS images (high temporal resolution images that allow tracking of changes in the landscape over time), and news reports. Volunteers continuously updated the 'fire range' that was used in official reports. The crisis map also provided important information about the location of the fire, the evacuation order, and the emergency shelter location.
7	Russia 2010 Russian forest fires [42]	Bloggers crowdsourced information from disaster sites to create crisis maps that showed where the fire had broken out, and also the water, food, medical care and other information needed for local relief efforts, turning the platform into a 'help map'.
8	Indonesia (3 flood seasons between 2013–2016) Flood in Jakarta [45]	The PetaJakarta.org system was deployed to aggregate the locations and conditions of local flood events reported by the public via social media and to generate an open real-time map of the city's flood situation.
9	Thailand 2011 Thailand Flood [6]	The public uses Twitter to disseminate and obtain information about flood hazards, including timely situational information, early warning forecasts, support notices, and resource requests. More influential Twitter users include disaster-related government agencies and NGOs, and people can choose the source of information they will track during a disaster in order to obtain timely and credible information.
10	Australia 2011 Queensland Flood [7]	The Australian Broadcasting Corporation released the Queensland Flood Crisis Map where people can send GIS-related photos and videos via email, SMS, Twitter or the platform itself. By combining this information with existing geographic information, hydrological data, and local knowledge, organizations can reconstruct flood areas to map the scope of the flood.
11	USA 2013 An EF5 tornado (highest level tornado on the Fujita scale) in Moore, Oklahoma [8]	NWS Norman (the largest regional office of the US National Weather Service) runs an experimental Twitter account @NWS Norman. NWS Norman introduced a specific topic tag on Twitter to facilitate citizens and tornado observers to submit their dangerous weather reports and geotagged hail and tornado photos.
12	Taiwan 2009 Typhoon Morakot [46]	A group of netizens from the Taiwan Digital Culture Association set up an unofficial Morak network disaster reporting center, which reported current losses and demand in the storm-affected areas and nearby areas. Subsequently, the website was integrated and updated with the official disaster relief center. The website is combined with Google Maps, and residents waiting for rescue can post information such as the current location and the latest damage caused by severe rainfall and landslides on the map.

4. Results

4.1. Self-Organizing Operation Mechanisms of Crowdsourcing in the Disaster Context

Through an analysis of the 12 case studies, we theorize crowdsourcing as containing three key elements: crowdsourcing platform(s), initiator(s) and contractor(s). The self-organizing operation mechanisms of crowdsourcing are realized through the multi-directional interaction between the crowdsourcing platform, the initiator, and the contractor, as shown in Figure 1 and Table 2.

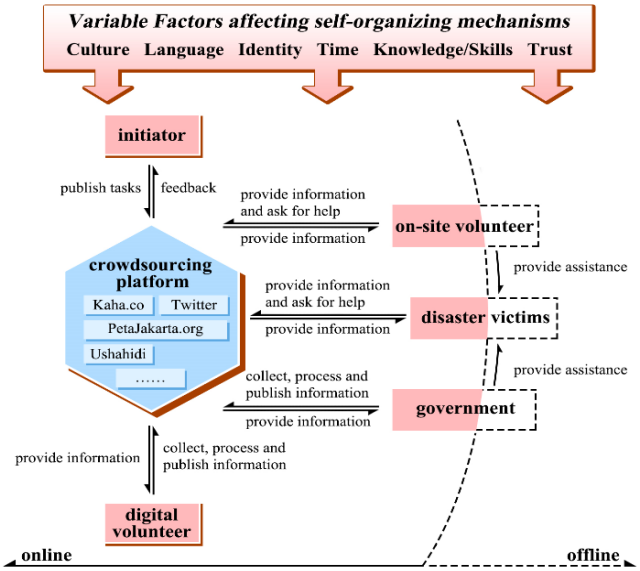

Figure 1. The Self-organizing Operation Mechanisms of Crowdsourcing in the Disaster Context.

Table 2. The Responsibilities and Tasks Undertaken by the Various Actors.

Type	Actors	Responsibilities	Tasks undertaken
Initiator	Government, NGO, business, individual	• Initiates crowdsourcing tasks • Gets feedback on crowdsourcing tasks • Releases disaster information	• Initiates actions to be undertaken • Sends and collects information through crowdsourcing platforms • Takes a strategic overview of disaster preparedness and mitigation • Integrates and utilizes online information to support offline disaster response
Contractor	**On-site volunteers:** any person present at the disaster scene; could be Government, NGO, business, individual members of the public	• Use their geographical and information advantages to feed first-hand information of the disaster scene into the crowdsourcing platform	• Inputs real-time information from the scene • Obtains attention for specific issues (e.g., casualties, severe damage, lack of medical care) • Requests manpower and materials to assist the victims
	Digital volunteers: come from all over the world and have different knowledge backgrounds, use crowdsourcing platforms to help with disaster actions	• Use their digital knowledge to support a range of disaster-reduction tasks	• Advise on disaster governance online • Act as contractors, by undertaking a range of disaster-related tasks • Discussing, suggesting and forwarding information related to disaster events • Tagging, categorizing, sorting, and translating crowdsourced raw data • Interpret data to generate structured and high-quality conclusions
	Disaster victims: direct victims of the disaster	• Leverage their geographic and informational advantages to provide first-hand information from the disaster scene	• Give real-time reports to the crowdsourcing platform of their disaster situation, including their location • Highlight assistance and medical needs for themselves and others
	Government: government employees	• Provide the public with verified information • Provide journalists with verified information • Provide verified information to the crowdsourcing platform	• Process and release information about disasters • Verify information, using support from the crowdsourcing platform

Figure 1 outlines the six variable factors that affect self-organizing mechanisms within the CAS—culture, language, identity, time, knowledge/skills, and trust. These variable factors emerged from the case study method and are crucial to understanding the unique complex adaptive system. The individual culture of the disaster system must be understood—for example, local community leaders had to be involved in disaster arrangements in Indonesia in order to ensure community approval. Language can have a huge impact upon the ability to process data, for example, there are semantic challenges from grammar and use of language from processing tweets and other digital data [45], as well as the ability of actors to communicate with each other. Online volunteers have their own identity—The Standby Task Force (SBTF), a worldwide volunteer community of digital volunteers promote themselves as 'digital humanitarians' [41]. The case studies also showed that crowdsourcing participants may undertake different roles and different identities in online and offline space. The knowledge, skills, and time that volunteers contribute to the system depend on individual variations. Finally, trust is an essential, but a variable, aspect of the system—there is no guarantee that the data that is provided is accurate, but successful crowdsourcing systems find a way to validate data for veracity [44]. Furthermore, social media and disaster apps hold the potential to not only be useful tools in disaster communication between citizens and authorities based on existing trust, but they also have the ability to help in building, rebuilding, or strengthening trusted relationships [47].

The roles undertaken by the key actors in Figure 1-initiator, digital volunteer, onsite volunteer, victims, and the Government are discussed in Table 2. These actors are adaptive subjects of the disaster response system with crowdsourcing intervention. They are self-adaptive and they can make decisions and complete tasks independently, and they can change their behavior rules based on previous behavior effects in order to benefit from crowdsourcing platforms.

In the analysis of the 12 case studies, crowdsourcing platforms are divided into two categories. One, platforms that are specifically designed for crowdsourcing, such as Ushahidi (a social activism and public accountability platform that has been used 150,000 times in over 160 countries), PetaJakarta.org (open-source, community-led platform to collect and disseminate information about flooding in Jakarta), or kaha (Nepalese crowdsourcing platform). Second, pre-existing social media platforms, such as Blogs, Weibo, YouTube, Facebook, and Twitter that are used for disaster-related information exchange and crowdsourcing.

The crowdsourcing platform breaks 'time and space' limitations of resource integration and is the key element of crowdsourcing self-organizing mechanisms because it facilitates a 24-h, 7 day-a-week focus on disaster reduction activity. The crowdsourcing platform provides a channel for self-organization, enabling disaster information exchange, which provides information support for NGOs, victims, and other members of the public to offer mutual assistance and help. At the same time, crowdsourcing platforms can also become tools for governments to collect and release disaster information to guide public opinion and to enable digital volunteers from all over the world to help after a disaster [48].

4.2. Crowdsourcing Structure and Self-Organizing Processes

The five CAS concepts proposed by Coetzee et al. (2016) [32] can be used to explain the self-organizing processes in crowdsourcing.

(1) Non-linearity: this is an essential concept for understanding the system because the inputs into the system may not result in proportionate expected outputs. For example, Tornados in the US develop with extremely short lead times, and despite sophisticated sensor technologies, the national false alarm rate was 76%, leading to misleading public communication. The public's direct observation of tornado development is an additional valuable information source for the National Weather Service information infrastructure for detection and prediction of tornados [8].

(2) Aggregation: across all the 12 case studies individuals formed their own groups. These can be on the basis of news interest (the Australian Broadcasting Corporation launched their own crisis map using their strong public outreach ability [7]), digital and disaster interest (the Standby Taskforce

formed as a group of international volunteers who are interested in supporting disaster relief [41]) or digital mapping skills [42]. Similarly, ordinary citizens with an interest in storms are able to use social media to amass large numbers of Twitter followers and form communities of interest, such as TornadoTitans and TxStorm Chasers on Twitter [8].

(3) Emergent behavior: remote digital specialists and Jakarta community members who were operating at the individual level, quickly led to changes in system-level properties where they ended up working directly with Twitter to enable data download of all current and historical references to floods in Jakarta [45]. Similarly, in the 2011 Queensland floods in Australia, the Australian Broadcasting Corporation combined GIS-related photos and videos of the crisis with existing geographic information, hydrological data, and local knowledge to map the scope of the flood, while the Queensland Government gained access to (normally restricted) satellite imagery from worldwide government and commercial agencies [7]. Thus, individual actors can use crowdsourcing to obtain national and international information, which impact on the whole system.

(4) Feedback loops and adaptation: when telephone emergency reporting systems failed after the Haiti disaster, a new feedback loop was created to develop a system for people to send free low-bandwidth SMS messages about their disaster needs [41].

(5) Context-base responses: the importance of context is essential to the functioning of each unique system. For example, the Chinese government's regulatory framework has impeded volunteers from crisis mapping in China because private mapping is unlawful [40]. In addition, Peta Jakarta was adapted to include crowdsourcing systems that were already being used by the community [45].

These five elements help frame the application of crowdsourcing in disaster governance and how crowdsourcing changes the traditional hierarchical structure of command and control, and forms a networked structure of connection, communication, collaboration, and openness, which is more flexible than the hierarchical structure and enables the actions of response subjects to adapt to the rapidly changing disaster environment. As shown in Figure 2 which derived from our analysis, the new crowdsourcing structure does not replace the traditional hierarchical structure but superimposes on the original structure to form a multi-directional interactive network, forming a multi-level, non-linear, open, and interactive complex structure. Its nodes represent different crowdsourcing subjects, and the government, like the public, is only one of them. If the government fails, it will not affect the operation of crowdsourcing. The links between nodes are created during the interaction between subjects and represent the complexity of feedback loops and adaptation. Feedback loops can be abstract and immaterial (disaster reports, loss information, medical needs, crisis information), and real and material (human resources, water, food, tents, and other supplies). Crowdsourcing enables a multi-directional flow of resources and information that is carried out outside the formal communication and power lines within a strict hierarchical organization. In essence, self-organization is a collective process in which all subjects in a system communicate, choose, and adjust their behaviors with respect to common goals [1]. In this process, different subjects form structures with many interactive links that pass energy, resources, and information to each node. The application of crowdsourcing helps to promote the self-organization process of each subject in disaster response.

4.2.1. Strengthen Communication and Coordination

Coordination means that the subject combines its actions with the actions of other relevant actors or organizations to achieve a common goal. Coordination capacity depends on effective communication, and if the communication process does not make the actors fully aware of common priorities for action, the possibility of achieving coordination among multiple actors is greatly reduced [49]. In a dynamic environment, timely and accurate information communication between the various subjects in the system is essential to maintain the flexibility of self-organization [1]. In disaster events, government agencies, NGOs, individual volunteers, and other response subjects need timely and accurate disaster information to response rapidly. They also need good communication and coordination to improve the efficiency of disaster reduction. Faced with the problem of gathering and matching a large number

of manpower, materials, and funds in disaster events, the efficiency of disaster governance will be greatly reduced if there is no effective communication and coordination between response subjects and between subjects and affected communities. Crowdsourcing has changed the way information is communicated, from traditional one-to-one or one-to-many to many-to-many. A person can play the role of information producer, transmitter and consumer at the same time. The application of crowdsourcing can, to a certain extent, promote the communication and coordination between response subjects and between them and affected communities, and improve the efficiency of resource matching.

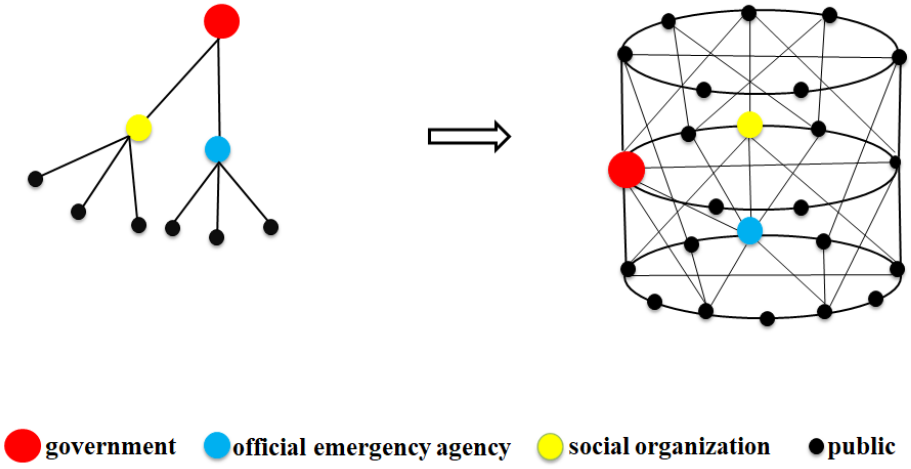

Figure 2. Transformation from a Traditional Hierarchical Structure to the Crowdsourcing Network Structure.

In the 2008 Wenchuan Earthquake, a QQ group named 'Home of the volunteers' published information about the disaster, coordinated the delivery of relief materials and connected a large number of rescue workers, volunteers, and resources within and outside the disaster area [40]. At its peak, the virtual community gathered more than 200 active volunteers and coordinated more than a third of Sichuan's civilian organizations in disaster relief efforts [40]. They realized a positive interaction with the government-led emergency and disaster reduction mechanisms and carried out the self-organized and orderly disaster reduction activities to make up for the deficiency of government disaster action. Similarly, during the devastating floods in Thailand in 2001, Twitter was used to disseminate and obtain flood-related information, including timely disaster information, early warning, support notices, resource requests, complaints and recommendations [46]. By mining and analyzing Twitter messages, government agencies or related organizations can better coordinate, manage, and plan disaster reduction efforts. During the Morak disaster, the capacity of Taiwan's official communication system was seriously inadequate [46]. The government did not know that there were hundreds of survivors in the mountains of Kaohsiung County until the media reported it. Government agencies were unable to understand the extent of the damage caused by the typhoon nor to pinpoint where people were trapped after the storm. The emergence of the unofficial Morak network disaster reporting center enabled the victims to have channels to report their own difficulties and locations, and the possibility of victims receiving rescue greatly increased.

4.2.2. Optimize Emergency Decision-Making

Natural disaster emergency decision-making is a dynamic process in which decision-makers make full use of existing information and resources to seek the best solution to a natural disaster. Good emergency decisions help the system self-organize in the right direction. When a natural disaster occurs, the decision-making body must collect and process disaster information quickly, define specific problems and objectives, formulate emergency action plans, organize the implementation and test the effectiveness, and continuously correct errors until the problem is solved. However, natural disasters

have considerable randomness and multidimensionality. Various situational factors, including the natural environment, social psychology, and production activities, interweave with each other and affect the current situation and the development path of disasters in real-time, affecting emergency decision-making. Therefore, decision-makers need to perceive the disaster and its changes in real-time, optimize the layout of governance and make dynamic adjustments. The timely, comprehensive and visualization of disaster information is particularly important. The existing disaster information collection work is completed by the government administrative system, which ensures the quality and credibility of the data in the mechanism. However, there are constraints, such as a long working cycle and slow updating speed. Through the open network structure of crowdsourcing, participation in disaster information acquisition is expanded from the government to the public. The public is the most direct and sensitive perceiver and provider of disaster information. The participation of the public expands the coverage of disaster governance, provides information on areas that are difficult for the government to cover comprehensively, and strengthens the timeliness and effectiveness of disaster governance.

Through crowdsourcing, real-time disaster information can be collected, verified, analyzed, and utilized by the public to generate visual crisis maps to help emergency response organizations or volunteers make timely and effective decisions with limited time and resources. In the events of the Haiti Earthquake, the Great East Japan Earthquake, the Wildfire in Santa Barbara County, and the Russian forest fires, crisis maps were drawn using crowdsourced data. The maps not only show the location of the disaster, but also include health care, trapped people, shelter, food needs, and other information. Using these crisis maps, policymakers can make better emergency response decisions and more accurately match disaster reduction resources based on the real-time needs of victims.

4.2.3. Improve the Ability to Learn and Adapt

In the process of self-organization, the learning ability of each subject depends on open communication channels and clear feedback patterns within the system, as well as the relationship between the system and its environment [1]. The openness and dynamics of crowdsourcing promote the communication and feedback between the various subjects and enhance the interaction between the subjects and the surrounding environment. Through the identification and acquisition of information, as well as the accumulation of knowledge and experience, disaster response subjects can continuously learn and adapt to the environment to better cope with disasters.

In Jakarta, Indonesia, the public reported the location and situation of local flood events to the crowdsourcing platform PetaJakarta.org via social media [45]. By sharing information with each other, the public became more aware of the threat of floods. The Jakarta disaster management authority noted that since the creation of PetaJakarta.org, the public has begun to pay more attention to disaster information-before it they often ignored disaster warnings [45]. The public's ability to learn and adapt to disasters is enhanced in the interaction with crowdsourcing platforms. When faced with another disaster, they are more likely to make the first response autonomously, which is more sustainable than just waiting for government assistance. After a disaster, relevant organizations can make full use of valuable crowdsourcing data to learn from and accumulate experience in disaster response, so as to improve relevant measures to reduce the risk of future disasters. Organizational learning means improved action through better knowledge and understanding, which in turn contributes to improved problem-solving abilities [50]. Crowdsourcing can help individuals or organizations continue to learn and contribute to sustainable disaster governance.

5. Discussion and Conclusions

Through a conceptual framework of CAS and the analysis of 12 crowdsourcing case studies, it is found that the self-organizing operation mechanisms of crowdsourcing are realized through the multi-directional interaction between the crowdsourcing platform, the initiator(s) and the contractor(s). Crowdsourcing is a networked structure of dynamism, connection, communication, collaboration and

openness that is more flexible than a traditional hierarchical governance structure so that the actions of response subjects can adapt to the rapidly changing disaster environment.

From a micro perspective, each subject in crowdsourcing in a disaster context is self-adaptive, and they can make decisions and complete tasks independently, and can change their behavior rules based on the effects of previous behavior in order to benefit from crowdsourcing platforms. In the macro aspect, the crowdsourcing system composed of various subjects develops in the interaction between subjects and between subjects and the environment, showing various complex evolutionary processes of the macro system, such as the cooperation of subjects to complete a complex disaster reduction task. The adaptive, self-organizing and nonlinear characteristics of crowdsourcing systems are common attributes of CAS. Therefore, it is a feasible approach to study crowdsourcing in the disaster context based on CAS.

The open structure of crowdsourcing facilitates the communication, selection, and behavior adjustment among the various actors in the disaster response system with respect to common goals, that is, it facilitates the self-organizing process in three main ways. Firstly, the application of crowdsourcing can, to a certain extent, promote the communication and coordination between response subjects, and between them and affected communities to improve the efficiency of resource matching. Secondly, through crowdsourcing, real-time disaster information can be collected, verified, analyzed, and utilized by the public to help the response subject make timely and effective decisions under the constraints of short timeframes and limited resources. Thirdly, crowdsourcing helps disaster response subjects to identify and absorb information, accumulate knowledge and experience, and continuously learn and adapt to the environment to better cope with disasters. Ultimately, improving disaster resilience is about building the systems' self-organizing capabilities. The application of crowdsourcing can promote the self-organization of disaster response systems, and therefore, promote disaster resilience.

Self-organization and adaptability in disaster systems have become hot topics. Comfort and Zhang (2020) recently used CAS theory as an analytical framework to identify operational networks that were adapted in real-time to current emergency environments during the 2008 Wenchuan Earthquake and the 2013 Lushan Earthquake [51]. Their findings are similar to ours, showing that the use of information technology makes real-time communication and adaptive behavior possible, and that self-organized disaster action increases the flexibility of disaster response. Similarly, Sukhwani and Shaw (2020) explored crowdsourcing in India and came to a similar conclusion: the lack of real-time disaster data often limits the ability of decision-makers to respond to disaster situations. Therefore, in some developing countries, limited economic resources mean that the application of information technology as a way to work efficiently with disaster information is particularly important [52].

This paper discusses how crowdsourcing can promote disaster resilience from the perspective of the CAS, which has its own unique context-based elements. It enriches the theoretical research on crowdsourcing and disaster resilience. There are some limitations of this study. As discussed in the methodology, the retrieval results exclude meeting minutes, book chapters and book reviews, and do not include news reports and government documents within the research scope, which reduces the research knowledge base. However, by undertaking a qualitative method, this paper has enabled the exploration of an understudied topic. Further research could focus on three core areas:

(1) The six variable factors that affect self-organizing mechanisms within the CAS—culture, language, identity, time, knowledge/skills, and trust—should be explored further. The qualitative method used in this paper illuminates core themes, which would benefit from further qualitative and quantitative studies into the complex adaptive systems for natural disasters.

(2) The successful operation of crowdsourcing mechanisms cannot be separated from the active participation of the public. Further in-depth theoretical and practical analysis is needed of the various subjective and objective factors that enable public participation in contributing crisis information in disaster events through crowdsourcing. In particular, we advocate further research into the complex online and offline identities of the crowdsourcing actors in their involvement in natural disasters.

(3) With the ever-increasing amount of data in the era of 'big data' bringing more complexity to managing natural disasters, disaster governance is faced with more opportunities and challenges. The successful operation of crowdsourcing mechanisms cannot be separated from developments in technology such as artificial intelligence. In disaster governance, the mechanisms for clustering, processing and coordinating crowdsourced data will inevitably be transformed through artificial intelligence that will automate and analyze complex natural disaster datasets at speeds considerably faster than humans. Therefore, future research should consider localized crowdsourcing platforms based on different countries' actual disaster-prone situations, in relation to developing technology that can be utilized to process complex information in faster and more effective ways.

Author Contributions: Conceptualization, H.Z. and Z.S.; Methodology, Z.S. and H.Z.; Writing-original draft preparation, Z.S., H.Z. and C.D.; Writing-Review and Editing, C.D., H.Z. and Z.S.; Visualization, Z.S., H.Z and C.D.; Supervision, H.Z. and C.D.; Funding acquisition, H.Z. and C.D. All authors have read and agree to the published version of the manuscript.

Funding: This research was funded by the Chinese National Social Science Foundation, grant number 16CGL061, and the Economic and Social Research Council (ESRC), UK.

Acknowledgments: The authors send their appreciation to Minggang Peng from Guangzhou University of China for his encouragement and advice on how to improve this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Comfort, L.K. Self-organization in complex systems. *J. Publ. Adm. Res. Theory* **1994**, *4*, 393–410.
2. Estellés-Arolas, E.; González-Ladrón-De-Guevara, F. Towards an integrated crowdsourcing definition. *J. Inf. Sci.* **2012**, *38*, 189–200. [CrossRef]
3. Wells, K.B.; Springgate, B.F.; Lizaola, E.; Jones, F.; Plough, A. Community engagement in disaster preparedness and recovery: A tale of two cities—Los Angeles and New Orleans. *Psychiatr. Clin. North Am.* **2013**, *36*, 451–466. [CrossRef] [PubMed]
4. Baybay, C.S.; Hindmarsh, R. Resilience in the Philippines through effective community engagement. *Aust. J. Emerg. Manag.* **2018**, *34*, 65–70.
5. Sokolov, A.; Verevkin, A. *Digitalization and Evolution of Civic Engagement: New Ways of Participation in Public Policy, International Conference on Digital Transformation Global Society*; Springer International Publishing: Geneva, Switzerland, 2016.
6. Kongthon, A.; Haruechaiyasak, C.; Pailai, J.; Kongyoung, S. The role of social media during a natural disaster: A case study of the 2011 Thai Flood. *Int. J. Inn. Tec. Manag.* **2014**, *11*, 1–12. [CrossRef]
7. McDougal, K. Using Volunteered Information to Map the Queensland Floods. Available online: https://eprints.usq.edu.au/20272/5/McDougall_SSSC2011_PV.pdf (accessed on 20 November 2019).
8. Chatfield, A.T.; Brajawidagda, U. Crowdsourcing hazardous weather reports from citizens via twittersphere under the short warning lead times of EF5 intensity tornado conditions. In Proceedings of the 47th International Conference on System Science, Waikoloa, HI, USA, 6–9 January 2014; IEEE: Waikoloa, HI, USA, 2014; pp. 2231–2241.
9. Howe, J. The rise of crowdsourcing. *Wired Mag.* **2006**, *14*, 1–4.
10. Degrossi, L.C. Flood Citizen Observatory: A Crowdsourcing-Based Approach for Flood Risk Management in Brazil. Available online: https://www.researchgate.net/publication/262939561_Flood_Citizen_Observatory_a_crowdsourcing-based_approach_for_flood_risk_management_in_Brazil (accessed on 2 January 2019).
11. Chu, E.T.; Chen, Y.L.; Lin, J.Y.; Liu, J.W.S. Crowdsourcing support system for disaster surveillance and response. In Proceedings of the 15th International Symposium on Wireless Personal Multimedia Communications, Taipei, Taiwan, 24–27 September 2012; IEEE: Taipei, Taiwan; pp. 21–25.
12. Ortmann, J.; Limbu, M.; Wang, D.; Kauppinen, T. Crowdsourcing Linked Open Data for Disaster Management. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.232.1448&rep=rep1&type=pdf#page=19 (accessed on 12 May 2019).
13. Schulz, A.; Paulheim, H.; Probst, F. Crisis information management in the Web 3.0 age. In Proceedings of the 9th International ISCRAM Conference, Vancouver, BC, Canada, 13–15 April 2012; pp. 1–5.

14. Hughes, A.; Palen, L. Twitter adoption and use in mass convergence and emergency events. *Int. J. Emerg. Manag.* **2009**, *6*, 248–260. [CrossRef]
15. Mejri, O.; Menoni, S.; Matias, K.; Aminoltaheri, N. Crisis information to support spatial planning in post disaster recovery. *Int. J. Disaster Risk Reduct.* **2017**, *22*, 46–61. [CrossRef]
16. Yuan, F.; Liu, R. Feasibility study of using crowdsourcing to identify critical affected areas for rapid damage assessment: Hurricane Matthew case study. *Int. J. Disaster Risk Reduct.* **2018**, *28*, 758–767. [CrossRef]
17. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Shinozuka, M.; Tierney, K.; Wallace, W.; Winterfeldt, D.V. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra.* **2003**, *19*, 733–752. [CrossRef]
18. Yang, D.; Zhang, D.; Frank, K.; Robertson, P.; Lichtenstern, M. Providing real-time assistance in disaster relief by leveraging crowdsourcing power. *Pers. Ubiquitous Comput.* **2014**, *18*, 2025–2034. [CrossRef]
19. Careem, M.; Silva, C.D.; Silva, R.D.; Raschidt, L.; Weerawarana, S. Sahana: Overview of a disaster management system. In Proceedings of the 2006 International Conference on Information and Automation, Qingdao, China, 15–17 December 2006.
20. Gao, H.; Wang, X.; Barbier, G.; Liu, H. Promoting coordination for disaster relief—from crowdsourcing to coordination. In *Social Computing, Behavioral-Cultural Modeling and Prediction. SBP 2011. Lecture Notes in Computer Science*; Salerno, J., Yang, S.J., Nau, D., Chai, S.K., Eds.; Springer: Berlin, Germany, 2007; Volume 6589, pp. 197–204.
21. Ludwig, T.; Kotthaus, C.; Reuter, C.; Dongen, S.; Pipek, V. Situated crowdsourcing during disasters: Managing the tasks of spontaneous volunteers through public displays. *Int. J. Hum. Comput. Stud.* **2017**, *102*, 103–121. [CrossRef]
22. Freifeld, C.C.; Chunara, R.; Mekaru, S.R.; Chan, E.H.; Kass-Hout, T.; Iacucci, A.A.; Brownstein, J.S. Participatory epidemiology: Use of mobile phones for community-based health reporting. *PLoS Med.* **2010**, *7*, 1–5. [CrossRef] [PubMed]
23. Kryvasheyeu, Y.; Chen, H.; Obradovich, N.; Moro, E.; Hentenryck, P.V.; Fowler, J.; Cebrian, M. Rapid assessment of disaster damage using social media activity. *Sci. Adv.* **2016**, *3*, 1–11. [CrossRef] [PubMed]
24. Paton, D.; Millar, M.; Johnston, D. Community resilience to volcanic hazard consequences. *Nat. Hazards* **2001**, *24*, 157–169. [CrossRef]
25. Timmerman, P. *Vulnerability, Resilience and the Collapse of Society: A Review of Models and Possible Climatic Applications*; Canada University of Toronto: Toronto, ON, Canada, 1981; pp. 124–186.
26. Paton, D.; Johnston, D.; Smith, L. Responding to resilience and adjustment adoption. *Aust. Manag.* **2001**, *16*, 47–52.
27. Cutter, S.L.; Barnes, L.; Berry, M.; Burton, C.; Evans, E.; Tate, E.; Webb, J. A place-based model for understanding community resilience to natural disasters. *Glob. Environ. Chang.* **2008**, *18*, 508–606. [CrossRef]
28. Coles, E.; Buckle, P. Developing community resilience as a foundation for effective disaster recovery. *Austra. J. Emerg. Manag.* **2004**, *19*, 324–1540.
29. Norris, F.; Stevens, S.P.; Pfefferbaum, B.; Wyche, K.; Pfefferbaum, R. Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *Am. J. Community Psychol.* **2008**, *41*, 127–150. [CrossRef]
30. Castleden, M.; Mckee, M.; Murray, V.; Leonardi, G. Resilience thinking in health protection. *J. Public Health* **2011**, *33*, 369–377. [CrossRef]
31. Manyena, S.B. The concept of resilience revisited. *Disasters* **2006**, *30*, 434–450. [CrossRef] [PubMed]
32. Coetzee, C.; Van Niekerk, D.; Raju, E. Disaster resilience and complex adaptive systems theory: Finding common grounds for risk reduction. *Disaster Prev. Manag.* **2016**, *25*, 196–211. [CrossRef]
33. Holland, J.H. *Hidden Order: How Adaptation Builds Complexity*; Leonardo, Addison-Wesley, Reading Mass: Cambridge, MA, USA, 1995; pp. 114–216.
34. Comfort, L.K. Coordination in rapidly evolving disaster response systems: The role of information. *Am. Behav. Sci.* **2004**, *48*, 295–313. [CrossRef]
35. Weick, K.E. The collapse of sensemaking in organizations: The Mann Gulch Disaster. *Adm. Sci. Q.* **1993**, *38*, 628. [CrossRef]
36. Benbasat, I.; Goldstein, D.K. The case research strategy in studies of information systems. *MIS Q.* **1987**, *11*, 369–386. [CrossRef]

37. Elsbach, K.D.; Cable, D.M.; Sherman, J.W. How passive 'face time' affects perceptions of employees: Evidence of spontaneous trait inference. *Soc. Sci. Elec. Pub.* **2010**, *63*, 735–760. [CrossRef]
38. Eisenhardt, K.M. Making fast strategic decisions in high-velocity environments. *Acade. Manag. J.* **1989**, *32*, 543–576.
39. Kohlbacher, F. *The Use of Qualitative Content Analysis in Case Study Research*; Forum: Qualitative Social Research: Vienna, Austria, 2005; Volume 7, Available online: http://nbn-resolving.de/urn:nbn:de:0114-fqs0601211.www.qualitative-research.net (accessed on 20 January 2020).
40. Peng, L. Crisis crowdsourcing and China's civic participation in disaster response: Evidence from earthquake relief. *China Inf.* **2017**, *31*, 327–348. [CrossRef]
41. Liu, S.B. Crisis crowdsourcing framework: Designing strategic configurations of crowdsourcing for the emergency management domain. *Comp. Sup. Coop. Work.* **2014**, *23*, 389–443. [CrossRef]
42. Meier, P. Crisis mapping in action: How open source software and global volunteer networks are changing the world, one map at a time. *J. Map Geogr. Libr.* **2012**, *8*, 89–100. [CrossRef]
43. Park, C.H.; Johnston, E.W. A framework for analyzing digital volunteer contributions in emergent crisis response efforts. *New Media Soc.* **2017**, *19*, 1308–1327. [CrossRef]
44. Goodchild, M.F.; Glennon, A.J. Crowdsourcing geographic information for disaster response: A research frontier. *Int. J. Digit. Earth* **2010**, *3*, 231–241. [CrossRef]
45. Ogie, R.I.; Clarke, R.J.; Forehead, H.; Perez, P. Crowdsourced social media data for disaster management: Lessons from the PetaJakarta.org project. *Comput. Environ. Urban Syst.* **2018**, *3*, 108–117. [CrossRef]
46. Huang, C.M.; Chan, E.; Hyder, A.A. Web 2.0 and internet social networking: A new tool for disaster management?—Lessons from Taiwan. *BMC Med. Inform. Decis. Mak* **2010**, *10*, 57–60. [CrossRef] [PubMed]
47. Appleby-Arnold, S.; Brockdorff, N.; Fallou, L.; Bossu, R. Truth, trust, and civic duty: Cultural factors in citizens' perceptions of mobile phone apps and social media in disasters. *J. Conting. Crisis Manag.* **2019**, *27*, 293–305. [CrossRef]
48. Starbird, K.; Palen, L. "Voluntweeters" self-organizing by digital volunteers in times of crisis. In Proceedings of the International Conference on Human Factors in Computing Systems, Vancouver, BC, Canada, 7–12 May 2011; ACM: New York, NY, USA, 2011; pp. 1071–1080.
49. Comfort, L.K. Crisis management in hindsight: Cognition, communication, coordination, and control. *Public Adm. Rev.* **2010**, *67*, 189–197. [CrossRef]
50. Lenart-Gansiniec, R.; Sułkowski, Ł. Crowdsourcing—A New Paradigm of Organizational Learning of Public Organizations. *Sustainability* **2018**, *10*, 3359. [CrossRef]
51. Comfort, L.K.; Zhang, H. Operational networks: Adaptation to extreme events in China. *Risk Anal.* **2020**. Available online: https://mp.weixin.qq.com/s/hVXlYD_4lc-O1xQxBWOiTA (accessed on 20 January 2020). [CrossRef]
52. Sukhwani, V.; Shaw, R. Operationalizing crowdsourcing through mobile applications for disaster management in India. *Prog. Disaster Sci.* **2020**, *5*, 1–9. [CrossRef]