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Review

Organizing Theories for Disasters into a Complex Adaptive System Framework

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Abstract: Increasingly urbanized populations and climate change have shifted the focus of decision makers from economic growth to the sustainability and resilience of urban infrastructure and communities, especially when communities face multiple hazards and need to recover from recurring disasters. Understanding human behavior and its interactions with built environments in disasters requires disciplinary crossover to explain its complexity, therefore we apply the lens of complex adaptive systems (CAS) to review disaster studies across disciplines. Disasters can be understood to consist of three interacting systems: (1) the physical system, consisting of geological, ecological, and human-built systems; (2) the social system, consisting of informal and formal human collective behavior; and (3) the individual actor system. Exploration of human behavior in these systems shows that CAS properties of heterogeneity, interacting subsystems, emergence, adaptation, and learning are integral, not just to cities, but to disaster studies and connecting them in the CAS framework provides us with a new lens to study disasters across disciplines. This paper explores the theories and models used in disaster studies, provides a framework to study and explain disasters, and discusses how complex adaptive systems can support theory building in disaster science for promoting more sustainable and resilient cities.

Keywords: cities; complex adaptive systems; computational social science; disasters; human behavior

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Citation: Burger, A.; Kennedy, W.G.; Crooks, A. Organizing Theories for Disasters into a Complex Adaptive System Framework. *Urban Sci.* **2021**, *5*, 61. https://doi.org/10.3390/urbansci5030061

Academic Editor: Sander Meijerink

Received: 9 July 2021
Accepted: 12 August 2021
Published: 16 August 2021

1. Introduction

The complex processes of urbanization that permeate the modern lives of today's growing global population are an ongoing challenge for city planners working to improve the health and well-being of urban populations. Today, the increasing frequency of reported disasters such as cyclones and floods [1] coinciding with the ongoing response to the COVID-19 pandemic [2] compound these challenges. For example, the number of people exposed to cascading hazards and disasters is expected to increase in the coming years due to urbanisation occurring in at-risk areas (e.g., flood plains) [1,3–8]. In order to minimize the impact of disasters for cities around the world, we need to better understand how individuals, families, and social systems operate under extreme conditions, how individuals and societies respond to disrupted complex social systems, and what can be done to aid those harmed by disasters [9]. Insights from research on disasters have been institutionalized and applied in new local, regional, and international strategies and tactics for mitigation, preparation and warning, emergency response and aid, recovery, resilience, and sustainability (e.g., [10–14]) at local, national, and global levels to reduce the risk of disruption and harm from disasters. The increasing frequency of disasters caused by climate change [1,5,15,16] has added a sense of urgency to disaster research while at the same time researchers in several fields, notably economics (e.g., [17]), socio-ecology (e.g., [18]), and human-coupled systems (e.g., [19]), have recognized the importance of framing human systems as complex adaptive systems and have begun to study their implications for global markets, climate change, and the organization of cities [20]. The application of complexity theory and complex adaptive systems has led to new conceptual tools for explanation in sustainability and urban studies research such as adaptive capacity (e.g., [21–23]), adaptive governance (e.g., [24]), spatial clustering of socio-economic groups (e.g., [25]), and a few notable works in disaster research have begun to explore its application to disasters both in discourse (e.g., [26]) and in practice (e.g., [27]). Research applying complex adaptive systems are currently beginning to be used to provide insights and address disasters such as the ongoing COVID-19 pandemic (e.g., [28,29]). Readers should note that there are a multitude of definitions of what constitutes a disaster, and it is not the purpose of this paper to discuss that issue, as it would distract from the main topic of the paper. However, readers are referred to example definitions such as those covered [30–34]).

In this paper, we propose an approach for exploring disasters using the lens of complex adaptive systems that can organize theories and provide explanation of the interactions and adaptations observed in disasters. Complex adaptive systems are nonlinear dynamic systems in which the interactions between individual elements and actors lead to emergent behavioral patterns and adaptation [35–37]. Nonlinear systems are those in which inputs and outputs of the system are not proportional to each other [38]. In the family of complex systems, complex adaptive systems are distinguishable by processes of adaptation including learning carried out by actors who respond to changes both inside and outside the system. System properties such as learning and adaptation in general lead to dynamics that include emergent behavior, flows of information, and system shifts between stability and instability (i.e., in and out of equilibrium). The emergent behavior results from interactions between individual components or subsystems, feedback loops, and self-organization [20,39]. Popular examples of complex adaptive systems include cities, ecosystems, and ant colonies, and the lenses of complex adaptive systems in these areas have led to discoveries such as the patterns of power laws and scaling in cities [20], the importance of heterogeneity for resilience of ecosystems [37], adaptive cycles in ecology and societies [40], and the role of self-organization in evolutionary biology [41].

The theme of complexity is already evident in disaster research (e.g., [42–45]), but complexity theory has only been directly applied in rare examples (e.g., [46–48]). Generally, theory, as used in disaster research, is built on case studies of disaster events and on statistics, both drawn from decades of data collection, not unifying theories. There are no unifying theories. Rather, we argue that the field is dominated by middle-ground theories such as uniformities of societal patterns following sequence patterns [49], therapeutic adjustments in disaster [30], patterns of pre-disaster growth and decline after a disaster [50], and social networks shrinking as disaster victims prioritize resources and energy [51]. The importance of a unifying general theory lies in its explanation of human behavior in disasters and the potential for prediction and knowledge of areas that could improve societal well-being. Overlaps of current theory in disasters and complex adaptive systems could point to the application of a new set of theories for application in disaster mitigation, preparation, management, and recovery as well as new methodological tools for the field of complexity science.

To determine whether applying theories of complexity and complex adaptive systems could support explanation of human behavior, within this paper we will explore three complex adaptive systems as evident from theories in disaster studies. These systems are: (1) the physical system (Section 2.1), consisting of geological, biological, meteorological, ecological, and human-built systems; (2) the social system (Section 2.2), consisting of formal and informal socio-cultural structures and collective behavior such as organizations and governments; and (3) the individual system (Section 2.3), consisting of the actor and its cognition.

Before we do, some terms and concepts need explanation. Collective behavior can be understood as the aggregated behavior of individuals in informal groups, families, or formal organizations. Individual actors in socio-ecological systems (i.e., physical systems) and collective behavior (i.e., social systems) have their own bio-physical and cognitive systems that process information and emotion before any identifiable behaviors and actions. Individual, goal-driven behavior drives actions and feeds bottom-up processes that reshape both the physical and social systems [20,38]. The social system is composed of individuals whose collective actions are aggregated into formal structures such as organizations and governments and informal behavior such as everyday actions evident in commuting, migration, and market demand. These social and cultural actions aggregate into larger forces that shape human and natural systems—for example, creating neighborhoods and setting aside wildlife sanctuaries. Physical dynamics in the geological, ecological, and human-built systems affect the conditions under which individual actors and groups behave, and the systems of collective behavior respond to and influence the shape of physical systems and the individual cognition of actors [52]. Each of these systems changes and adapts in response to internal processes and each other as part of a complex adaptive system of systems [38]. The interactions and adaptations of these systems produce nonlinear relationships with properties of aggregation, feedback, self-organization, emergence, diversity or heterogeneity, and flows of information, resources, and energy. According to Holland [35], the decision-making behavior and adaptation of the individual entities in the system build on and add to the complexity of the overall system, ultimately creating a "whole that is greater than the sum of its parts." Typically studied in separate disciplines, the integration of these systems into a complex adaptive system of systems may improve explanation of the phenomena and dynamics in disaster that interact and cut across systems and suggest new theory and sources for data that support explanation of human behavior.

A systematic review of theory in the disaster literature as presented in this paper will demonstrate the properties and dynamics of complex adaptive systems and how complexity theory is integral to understanding human behavior in disasters by addressing the interactions across systems. For the purpose of this paper, the main properties of complex adaptive systems are narrowed to the following: heterogeneity, webs of connections, relationships and interactions, and adaptations arising from individual actions, decisions, and learning. The paper is organized first to identify disaster theories that aligns with the three systems and test whether properties of complex adaptive systems exist (Section 2). We will then discuss the characteristics of a complex adaptive system and how complexity theory can be applied to disaster research in Section 3. Finally, we will summarize the findings and explore implications for future disaster research with an eye on sustainable and resilient cities (Section 4).

2. Background: Evolution of Disaster Research in Three Systems

To find evidence of how disasters can be viewed as complex adaptive systems, we focus our paper on social science theories, models, and frameworks that explain how people on the ground behave before, during, and after a disaster as it relates to the physical, social, and individual systems. Works specifically relating to emergency response management, risk management, and public communications in disasters were avoided because our research is targeting the underlying, bottom-up effects of human behavior in disasters rather than hierarchical, top-down, organized responses. Also, we do not explicitly look at the interactions between human and technological systems as we find that this is often implied in the literature, rather than studied directly (e.g., [53–56]). For those interested in research and theory on technological and organizational disasters and the interactions of individuals on the built system (i.e., infrastructure, etc.), we refer readers to [57–63]. In addition, there is a large body of work on current emergency and disaster management that includes literature reviews and curricula for the emergency management community (e.g., [64–67]). The intent of this review is to demonstrate how disaster theories, and frameworks have evolved so that we may understand the processes within disasters. Our goal is to lay the foundation for thinking of disasters in a complex adaptive systems framework (Section 3).

2.1. Physical Systems

The physical system, as defined in this paper, consists of geological, biological, meteorological, ecological, and human-built systems, and the dynamics within this system have always been present in disaster research. Early studies centered on extreme events that caused injury or the loss of life and property within the social and physical systems of cities and communities. These events were conceptualized as unforeseen, rare, and extreme interruptions in everyday life, and after a period of recovery and social change, activities would return to normal (see: [49,68–70]). Research during this period can be categorized by studies on specific forms of disaster (e.g., bombing, explosion, earthquake, tornado, hurricane, fire, or flood) and their social and psychological impact on individuals and communities. Although work between the 1930s and the 1950s was in its early stages, Wallace [70] collected a body of disaster studies and completed an interdisciplinary survey with contributions from the fields of psychiatry, general medicine, psychology, sociology, anthropology, economics, and political science. During this early period, disasters were often understood in the context of a trigger event within separate, external processes such as natural geophysical and meteorological phenomena, e.g., earthquakes, hurricanes, and tornados [71], human-made events such as famine, pestilence, war, or revolution [72].

Breaking from this approach, White [73] argued that disasters resulted from interactions between acts of "nature: and acts of "man." For example, White's [73] study of flooding disasters explored natural hazard and flood plain environmental features and their human occupation, corresponding social and economic policies, and behavioral adjustments to the flood plain. In a broader study of disruption from environmental extremes, Burton et al. [74] found disaster events resulted from a combination of physical and social processes in which communities adjusted their behavior based on perceptions of the environmental hazards. This was followed by the systemic framework of a hazardousness of place in a regional ecology [75], and a socio-ecological system model of an interaction process between man and nature [76]. Subsequent studies have shown that disasters occur at individual, group, and societal levels, and individuals collectively adjust and shape their environment at local, national and global scales (e.g., [50,77,78]) based on their perceived risk and in response to natural extremes. Barkun's [79] study of the systemic issues of temporal and spatial scales in disasters revealed that modern disasters were not constrained by spatial and temporal boundaries, but rather occurred across scales. For example, Typhoon Haiyun in 2013 triggered a top-down, organized international response to a regional disaster in the Philippines [80]. Local, bottom-up responses had significant roles in the case of the 2010 and 2012 earthquakes in Canterbury, New Zealand, even though they were found insufficient without external aid [81].

By the 1980s, conceptions of climatic vulnerability and resilience entered into the vernacular, and the understanding of disasters shifted from single events or type of hazard to ongoing processes and relationships (e.g., [82]). Natural disasters were coming to be considered the outcome of extreme geophysical processes and the failures of human systems to appropriately manage ongoing relationships with their habitats. A longitudinal review of large-scale disasters by O'Keefe et al. [83] revealed that geological changes could not explain the increasing costs and loss of life unless the population's vulnerabilities and socio-economic factors were also assessed. Timmerman [45] introduced the concept of risk and risk assessment, and he addressed how hazards stress the socio-ecological system, inducing adjustments and adaptations in the social system depending on periodicity. Social systems under continuous and periodic stress make permanent and temporary adjustments to continue functioning, such as in the case of annual flooding, while those systems that experience periodic stress only adjust to disasters of greater magnitude, such as in the case of building improvements to resist earthquakes. In mulitiple studies, Hewitt [82] showed that disasters were dependent on how social systems assess and adapt, avoid, or reduce the risk from hazards.

The significance of human contribution to losses of life and property in disasters was widely recognized by the 1990s, and studies on vulnerability accounted for social, cultural, economic, and political processes as well as the ongoing geophysical and biological processes that trigger natural disaster events. One such example is the Pressure and Release Model and the Access Model proposed by Blaikie et al. [84]. In these models, the focus was on the social vulnerabilities within a community rather than the hazard itself. These two models integrated top-down natural and social forces with bottom-up individual decision making of a population of actors, and they incorporated macro- and micro- mechanisms into the larger socio-ecological system. By studying the interconnections of natural and social systems, researchers began to analyze the interrelated and interdependent elements in the ecological research fields with respect to human sociocultural systems and ecological networks. The integration of ecological and social systems revealed interdependent relationships and adaptive strategies that evolved through selective forces to reduce vulnerability in disasters [85]. Cannon [86], using a similar systems approach, showed how the risks and opportunities in the environmental system are unevenly distributed throughout the population based on social power structures and can be analyzed through vulnerability maps. Mileti [13] used the human-coupled systems (or socio-ecological systems) approach to understand the complex interactions between the environment and human perceptions, actions, and organizations to introduce the concept of sustainable hazard mitigation with the objective of using sustainable community planning to reduce disaster losses.

New models such as Blaikie's et al. [84] and Mileti's conceptualizations of "sustainability" [13] reflected a shift in disaster issues from a paradigm of hazards and emergency to that of risk reduction and mitigation. Disaster events were no longer viewed as unusual and infrequent, but part of larger socio-ecological processes deeply rooted in local communities and embedded in complex adaptive systems (e.g., [87–90]). Such work also emphasized that when studying local- and regional-scale interactions, one should account for local memory and learning processes to address sustainability, risk reduction, and the adaptive capacity of these socio-ecological systems [91]. The work was subsequently extended to account for dynamically linked systems with structures, processes, feedback, nonlinearities, uncertainty, resilience, and entropy that signal a complex adaptive system's ability to self-organize and build capacity and to learn and adapt to recurrent disturbances and change (e.g., [92–99]). Within disaster research these effects have been explored as a community's adaptive capacity (e.g., [100–102]) and adaptive resilience (e.g., [98,103–106]). As a result, the application of system of systems and properties of complexity has increasingly appeared in the disaster literature (e.g., [46,48,94,98,107–112]). Work addressing complexity has spawned new areas for interdisciplinary theory such as relating critical infrastructure to society's feedback loops in cascading disasters [113]. Cascading disasters have been applied to new conceptual models of disaster, such as Cascading Hazards to disAsters that are Socially constructed eMerging out of Social Vulnerability (CHASMS) [114], that assess the complexities of cascading hazards and associated risks that lead to inequitable outcomes from disaster as a result of complex interactions arising from social vulnerability, health inequality, and environmental hazards. Models that recognize the complexity of human and urban systems are increasingly being used to understand disasters. However, these models do not extend the lens of complex adaptive systems to develop the necessary multi-faceted approaches required address the circumstances of disaster.

To summarize, the general body of disaster research on areas within the physical system has grown from treating each disaster as an isolated, unique, extreme event to the study of disaster events as part of larger socio-ecological and human-coupled system processes. As more data were collected, researchers were able to define elements of the social and the ecological systems and incorporate them into the context of a complex adaptive system (e.g., [88,115]), and this categorization has provided the language and metrics of causation in the midst of multi-scale dynamics, nonlinearity, and uncertainty. The interactions, interdependencies, processes, feedback, and learning of the physical system's elements have led to the conceptualizations of adaptive capacity and adaptive resilience. With this subsystem of disaster discussed, we now turn to the social side of disasters.

2.2. Social Systems

At the core of disaster research is the study of group behavior, and this section will focus on the social system and the behavior of groups, families, organizations, and communities underlying disaster response. Prince [69] was the first to document the disintegration of the social system, particularly governance and behavioral norms, in response to a disaster. His work established a central theory of disaster: with the crisis comes social chaos and then new forms of collective behavior, social relationships, and compositions ([69], p. 67) (see also: [116,117]). Later studies differentiated behavior based on the disaster's causation, whether "human-made", such as war and technological accidents, or "natural," such as disease epidemic, earthquake, or flood, and these events were viewed as infrequent and mitigated with better preparation and responses [70–72]. Similar to work on the physical system cited in the last Section 2.1, this early research was generally descriptive and concentrated on documenting basic behaviors (e.g., victim trauma, convergence of first responders to the area [69–71]). Importantly, this work dispelled disaster myths by establishing that panic was an infrequent behavior and requiring specific conditions and that emergency warnings could significantly affect behavior [71,118].

By the 1960s, more work led to the development of a number of disaster theories. One was Fritz's [30] theory of therapeutic adjustments in which the situational characteristics of the disaster along with community adjustments lead to a shared experience that provides physical and emotional support. He found that human behavior differentiated by the disaster's spatial zones, time periods, type of involvement (e.g., victim, national guard, medical professional), and the prior preparation and conditioning. Leeds [119] proposed that the cultural norm of giving replaced reciprocity in response to the social vacuums that arose. Anderson's [120] study of a 1964 Ohio River Valley flood found that repeated community adaptations created a subculture of learned organizational responses in norms, values, knowledge, and technology to cope with the physical system. In this specific case, community leaders in the Cincinnati area developed a set of emergency standby mechanisms and complex inter-organizational disaster plans to combat floods. Drabek and Boggs' [121] work identified that family ties had a significant effect on responses to warnings and the decision to evacuate, and Turner [122] proposed that mechanical and organic solidarity are enacted and used by community residents to provide emotional support and overcome disaster trauma. By the end of the decade, Barton [123] collated a comprehensive volume summarizing disaster theories of individual and collective behavior in response to extreme stress. Most notably, Barton [123] proposed a detailed model of the therapeutic community response that included the activation of a communication system, the willingness of victims to communicate the extent of deprivation, sympathetic identification with the victims, relative deprivation, blaming of the victims, a normative mechanism, and situational and motivational determinants of helping. With a relatively robust and growing body of studies, researchers were able to move away from simplistic explanation and models for behavior in disasters. New descriptive and explanatory theories were able to differentiate behavior found within the types and stages of disasters, and disaster research on collective behavior in the following decades built on these findings of behavioral differentiation.

The growing body of human behavioral data ultimately led to a challenge of the predominate conception of therapeutic community culture in disasters. Although it has been challenged in later research (e.g., [124,125]), Erikson's [126] study of the 1972 Buffalo Creek flood suggested that the disruption of social networks and neighborhoods could result in a collective trauma of fear, apathy, and demoralization. Further, longitudinal studies by Quarantelli and Dynes [127] showed that community cooperation frequently occurred early, but that conflict arose in the later stages due socio-cultural conditions. Oliver-Smith [128] explained this using in-group/out-group dynamics and varying patterns of social identification and interaction with evolving problems during the long processes of recovery and reconstruction. The characteristics of long, slow disaster processes, and long-term disruption and stress, such as those in technical disasters with chronic community stress, prevented the emergence of a therapeutic community [129,130]. In such instances, it was found that communities experienced a corrosive community process, characterized by blame assignment and evasive, unresponsive authorities [131]. Rather than creating therapeutic processes through cohesion and support, emergent groups become nonresponsive, competitive, and hostile.

To uncover the therapeutic and corrosive processes of social relationships, studies of informal relationships and social network effects entered broadly into disaster research around the 1980s. Up to this time, research on the social system had focused primarily on organizations and to a lesser extent on families. Drabek et al. [132] completed an in-depth study of kinship and friendship relationships that revealed exchanges in these relationships supported disaster recovery. These networks of relationships were shown to operate as parallel structures to formalized organizations. Later it was shown that families made decisions, determined disaster activities, and mediated the flow of information as a unit [133], and social networks were crucial to the early formation of emergent citizen groups [134]. Bolin [135] developed a preliminary model of family recovery based on levels of embeddedness in kin and institutional networks. A comparative case study of disasters by Bolin and Bolton [136] along the dimensions of disaster agents, ethnic groups, patterns of destruction, aid utilization, and victim recovery revealed complexities and variations in the process of disaster recovery, but also found that at all the disaster sites kin relationships provided morale and emotional support. In another social model, Bates [137] conceptualized modern society as a complex network of social systems which were later shown as linked through social mechanisms [138]. These enduring social relationships were again found to be the determinants of collective behavior in an application of emergent norm theory to evacuation behavior [139]. All of these studies indicate the significant role social relationships have played as both potential vulnerabilities and opportunities for support and adaptation in disasters.

Building on theories of therapeutic and chronic processes and effects of social relationships on human behavior in disasters, the 1990s can be characterized as a period of discovery and differentiation in which new details of human behavior were uncovered rather than a period of major advances in theoretical understanding. Researchers found that disaster phases were not necessarily sequential and did not uniformly affect an area [140]. Other work found that disaster vulnerability and response was situational, and analysis of vulnerability variables, gender, age, class, ethnicity, and disability revealed that individual hazard perception and behavior were constrained by existing relationships and power in social structures (e.g., [141–143]). Race, education, and age [144], gender [145–147], age and income [148,149], and ethnicity [150] have also been shown to differentially affect the experience of and recovery from disasters.

Disaster research in the 21st century has brought a surge of social theories and models that integrate underlying social, economic, and political processes, the interconnectedness of individuals and communities in resilience, and their complexity. Perhaps the most significant is the reconceptualization of citizens as resources rather than victims [151,152]. Numerous studies have argued that community resilience and local capacities are neglected in disaster planning and response (e.g., [153–155]). Dynes [156,157] incorporated social capital into the conceptualizations of communities in disasters. Nakagawa and Shaw [158] and Shaw and Goda [159] subsequently found that higher levels of social capital and collective action were associated with faster disaster recovery from the Kobe earthquake of 1995. Micro social networks have also been demonstrated to be important for disaster recovery and the evolution of institutions to solve post-disaster collective action problems [160], and varying forms of social capital in bonding, bridging, and linking social ties, could alter the effects of disaster resilience and recovery [161].

The local capacity of communities to prepare for, respond to, and recover from disasters is now embedded in new models of community resilience including Tobin and Whiteford's [162] structural-cognitive model, Rose's [97,106] economic model of inherent and adaptive resilience, Maguire and Hagan's [163] social resilience model, and Cutter et al.'s [100] widely adopted Disaster Resilience of Place (DROP) model. In such work resilience can be broadly understood as the ability to withstand stressors and return to normal activities. Norris et al. [105] found that community resilience emerges from four primary sets of adaptive capacities: economic development, social capital, information and communication, and community competence. Their work noted this requires intangible community capabilities such as flexibility, decision-making skills, and trust, while others have shown that resilient cities and communities are those that effectively activate formal and latent social connections for self-organization and local leadership (e.g., [164,165]). To account for the complexities in disasters, Pelling [91] developed a participatory framework of vulnerability and risk assessment that enables disaster risk reduction and management to cross scales from the global to the local. This framework allows for adaptive learning using local knowledge that empowers the local community in times of disasters. We see this in adaptive governance [166], in which key persons self-organize, develop common understandings and policies for ecosystem-based management, that has been applied to disaster resilience and risk reduction [167,168]. In an analysis of disaster risk reduction, Wisner et al. [169] confirmed the importance of these properties in disasters: multi-scale, top-down and bottom-up dynamics, outside specialist knowledge from many disciplines, and local knowledge. These theories, models, and frameworks integrate new conceptualizations of group behavior that include social capital and resilience, networks and learning, open and adaptive systems, adaptive capacity, and complexity.

Research on the social system in disasters has revealed complex processes of social interactions, at times cohesive and at other times divisive. Early work documented the basic behaviors in different types and stages of disasters (e.g., [30,70]), and these were later attributed to social norms of reciprocity, culture, family, and solidarity in crisis. Building on empirical studies, models of a therapeutic community response [123] and a corrosive community process [129] showed how collective behavior could become either cohesive or divisive. These processes could be present in the same disaster depending on the stage and duration of the disaster, socio-cultural conditions, and the quality of social relationships. Ultimately researchers developed complex theories that incorporated underlying social, economic, and political processes such as community resilience, adaptive governance, and social capital (e.g., [100,162,166]). Intersecting with Pescaroli and Alexander's [113] conceptualizations of cascading disasters, Mizrahi [170] suggests collective action can be incorporated into a dynamic framework of cascading disasters, information cascades, and continuous time models that can be used understand how common knowledge and social learning reshape cascading hazards and disasters. All of these current theories incorporate individuals in webs of relationships, physical, social, and individual, acting within complex adaptive system.

2.3. Individual Systems

The actors underlying the social system are individuals whose cognitive systems determine behavior and interactions with others and their environment, the physical and social systems. Early work on disaster theories of individual cognition and psychology arose from studies of population reactions to stresses in war and later to extreme weather events. For example, Wallace [70] called the dominant individual reaction a disaster syndrome, in which those affected were described as "shock", "dazed", "stupor", "apathy", "stunned" and "numbed" as a result of cognitive dysfunction that arose from disruption of their culture and routine behaviors. Killian [171] theorized that this led to conflict as individuals struggled to sustain the behaviors required for membership within social groups after a disaster. Empirical studies provided evidence of a mix of individual reactions in disasters. Specifically, Tyhurst [172] found that approximately 75% of individuals displayed symptoms of a stunned and bewildered lack of awareness or restricted field of attention, while 10-25% were confused, paralyzed, hysterical, or screaming, and 12–25% were cool and collected. Panic was also found to be an unlikely response to disasters [71], but rather manifested only under specific conditions [118]. To explain some of the variation, Glass [173] proposed individual psychological states at each stage: pre-impact (denial, adopts fatalistic concept, apathy, and training), warning (overactivity and flight), recoil (underactivity, apathy, disaster syndrome, or fatigue), and post-impact (grief, understanding of personal loss, anger, or resentment). In the post-impact stage, scapegoating was found to rise from a complex mix of frustration, fear, guilt, and latent hostility [174].

Further, Fritz [30] theorized that when disasters strike and social patterns and cultural norms are disrupted, individuals are forced to make critical choices within very short time-spans. Issues of survival, subsistence, shelter, and health take precedent over social order and meaning. Individual reactions to the perceived context differentiates their behavior in relation to location, time, involvement in the disaster, and preparation and conditioning. Crawshaw [175] provided empirical validation of these differentiated individual reactions and attributed them to the needs of individuals in specific age groups and family make-up. Simultaneously, Lazarus [176] proposed a psychological stress theory in which individuals engage in threat appraisal rather than anxiety arousal before engaging in coping mechanisms of actions to strengthen resources from harm, attack, avoidance, or defense. The theory was later modified to include cognitive appraisal with assessments of the person-environment transactions and problem- and emotion-focused forms of coping under stress [177,178]. Drabek and Boggs [121] found that individual behaviors and choices were heavily influenced by the warnings and evacuations of relatives and by their familial roles as parent, child, elder and younger family members.

In his summary review of disaster studies, Barton [123] attributed individual behavior to personal emotions, preferences, and role behavior in informal and formal organizations and deeper psychological and social norm explanations followed. Perry and Lindell [179] developed a conceptual model of inter-related factors with psychological consequences: the characteristics of the disaster, the characteristics of the social system, and the pre-impact characteristics of the individual. These factors included community preparedness, forewarning, scope and duration of impact, destruction of kin and friendship networks, extent of property damage, pre-impact psychological stability, grief reactions, disaster subculture, and existence of a therapeutic community and institutional rehabilitation. Mawson [180] proposed a theoretical model of social attachment to explain self-preservation and the lack of behavior in disasters and crises. In response to a threat or disaster, the typical individual seeks the proximity of familiar persons and places, and thus individuals do not flee from a disaster, but rather flee to social attachments. In the post-impact stage of disasters, a significant part of individual trauma was found to be the loss of these family members, community, and other social attachments [71,126,172].

Individual stress and behavior in disasters was not only attributed to psychological explanations of loss or change of social attachments, but also to the disruption of social norms and corresponding rules of behavior. Emergent norm theory [181] attempted to explain that when individuals encounter new situations, new norms can "emerge" spontaneously from ongoing social processes and events without reflection of existing social structure. However, societal norms continue to constrain individual behavior in times of stress [182], and individuals maintain these norms and extend their social roles to address the needs of a crisis [182]. Individual self-categorization [181] and social identity have been found to be significant in disaster behavior, explaining both emergent groups and affecting group solidarity [183] and provisions of aid [184]. Similarly, individual behavior research in the 1990s provided few new theories, but it did produce findings of both heterogeneous and homogeneous behavior at different times of the disaster. A meta-analysis of studies on psychopathology, psychological problems, and pathologies or impairments suffered by post-disaster victims [185] found significant heterogeneity in post-disaster responses. Individual responses varied by victim and disaster characteristics depending on the death rate/loss of social attachments, time elapsed from impact, and degree of human responsibility. A contrasting study by Goltz et al. [186] found that the rapid onset of disasters elicited more homogeneous responses with individual behavior motivated by fear and influenced by the presence of others. At the onset, individuals engaged in rational self-protective activities during an earthquake. These were survival-oriented, learned and adaptive responses from past experiences. Adaptive behavior also affected the social attachments of individual victims as they pruned their social networks in times of disaster to optimize energy and resources [51].

The significance of social attachments as an explanation of individual behavior was furthered in the 2000s. Hobfoll's [187,188] process-based theory, Conservation of Resources (COR), predicts that resource loss is the principal ingredient in the stress process and that individual stress is derived from attachments within families and intimates. These attachments were also found to protect individuals from psychological distress [189]. Mawson [190] revised his theory of social attachments and proposed that individuals balance the need to be close to affiliative attachments and far from physical threats. This social attachment theory was elaborated by Mawson [191] using a biopsychosocial approach based on stimulation-seeking and stimulation-avoidance behavior. "Panic", including flight, aggression, and other forms of intense agitation, results from intense stimulation-seeking behavior, activities that facilitate contact between an organism's sensory receptors and external objects, arising from a high level of arousal. Individual resilience and forms of capital, including social, are the latent measures of capacities and resources in the Resilience Activation Framework [54] which can be used to test how access to social resources promotes adaptations and coping mechanisms in crisis and disasters.

Disaster research in the 2000s also introduced new cognitive science approaches for explanation of individual behavior that focus on decision making within the broader context of survival, loss, and social norms. In a socio-cultural model, Paton [192] used multiple dimensions of risk assessment and preparation based on motivation and intention variables to provide explanation for disaster preparation behavior. Rosenstein [193] proposed an assessment for Decision-Making Capacity (DMC). Van Fenema [194] proposed collaborative elasticity, a collective capability to manage the unexpected in crisis, that leverages theories of individual cognition, distributed cognition, and the collective mind, and Ripley [195] emphasized cognitive responses to disasters and decision making in a survival arc of denial, deliberation, and decision before action. Leveraging work on decision making and game theory, Eiser et al. [196] proposed that individuals make decisions based on perceived risks in conditions of uncertainty, and Espina and Teng-Calleja [197] have recently applied social cognitive theory [198] to show how individual and environmental factors influence disaster preparedness. Individual interpretations of risk and actions in uncertainty are shaped by experience, personal feelings and values, beliefs, and interpersonal and social dynamics. In social cognitive theory, personal agency is regulated between direct and proxy agency (relying on others to act in one's interests), and collective agency (social coordination and interdependency). Extending social cognitive theory, Benight and Bandura [199] found that human agency and perceived coping self-efficacy affected an individual's recovery from trauma.

In summary, compared with the research on the social systems, theories of individual cognition and behavior in disasters (outside of emergency management and organizational theory) are not well integrated into the disaster literature. However, as occurred in the physical and social systems, there has been a pattern of initial observation and descriptive theory, then discovery of underlying explanation, and finally research that gradually leads to more complex theories. These theories have been posited from the perspective of roles and social norms (e.g., [181]) and psychology (e.g., [176]). Later theories integrated both of these areas in multi-dimensional analysis of inter-related factors (e.g., [179,192]) or delved into biopsychosocial approaches (e.g., [185,191]). The recent cognitive approaches to individual behavior bring all of these approaches into a decision-making framework that accounts for the effects of roles and social norms, social attachments, and biopsychosocial processes in disasters (e.g., [195,196]). It also provides explanation for individual behavior as an output of the human cognitive system, a complex adaptive system that incorporates, among other features, decision making, perception, reasoning, memory, emotion, and biology. Now having reviewed the complex adaptive nature of the physical, social, and individual systems of disasters, from here on we can directly consider disaster as a phenomenon within a complex adaptive system framework.

3. The Role of Complex Adaptive Systems in Disaster Research

In the previous sections, we reviewed disaster theories within three systems: the physical (Section 2.1), social (Section 2.2), and individual (Section 2.3). We specifically highlighted specific properties of complex adaptive systems: heterogeneity, webs of connections, relationships and interactions, and adaptations arising from individual actions, decisions, and learning. Along with these properties, a complex adaptive system contains feedback loops, patterns of self-organization, flows of information and resources, and system shifts between stability and instability (in and out of equilibrium). By definition, a disaster is a disruption of the social system after which components and actors of the system must adapt and readjust in order to return to some form of equilibrium. Our review found relatively few explanations of the interactions, processes, and feedback that cut across the three systems, other than that of Gunderson and Holling [88]. This gap can be addressed with explicit study of the interactions between subsystems through the lens of complex adaptive systems. Complexity science identifies a complex adaptive system as a system within which the interactions between individual elements and actors lead to emergent behavioral patterns and adaptation [35–37]. The properties and dynamics of complex adaptive systems are found in the physical system, the social system, and the individual system with cities being a exemplar [20].

To test whether disaster and complexity theory are integral to understanding human behavior in disasters, a systematic literature review of disaster theories was organized and discussed in Section 2. The following section provides a brief argument for how each of the systems can be linked (Section 3.1) building upon what was discussed in Section 2. This leads us to how the integration of these systems (i.e., physical, social and individual) exposes their interactions, and we introduce our framework of the intersecting complex adaptive systems of disaster (Section 3.2). Lastly, we discuss how concepts of complex adaptive systems and complexity science can be applied in disaster research (Section 3.3).

3.1. Linkages between the Physical, Social, and Individual Systems

Disasters are caused by a combination of physical and social processes. Early theories identified periods of stability, system disruption, and a return to stability as discussed earlier (Section 2.1). By the mid-1900s, the physical and social processes of disasters were recognized as being shaped by both individuals and society (e.g., [74]). Disasters were later recognized as events occurring across multiple scales (e.g., [79]). Interdependencies between the ecological (i.e., physical) and human (i.e., social) systems and adaptive strategies led to evolutionary change [85] such as seen in agroforestry processes in the Amazon (e.g., [200–202]). The adaptation and adjustments of a social system created varying hazards and risk profiles, and models of disaster illustrated how top-down and bottom-up processes affected disaster outcomes. The understanding of dynamically linked systems has led to current socio-ecological models in which disaster events occur within a complex adaptive system that learns and adapts in response to ongoing interactions. In this perspective the effects of individual and social system behavior in groups and organizations are critical factors for explaining behavioral response and resilience to disasters (e.g., [23,108]).

Collective behavior occurs as part of a social system (Section 2.2), whether it consists of informal groups, families, organizations, or communities, and these collective behaviors are the aggregate behavior of individuals who respond to disaster events. Behavioral responses are the result of both the physical effects of the disaster and the interactions in formal and informal social relationships. Modern disaster theories integrate these understandings of complex social, economic, and political processes aggregated from the interactions between community members in therapeutic and corrosive processes. They are now used to measure the capacity of communities to survive and recover from disaster events (e.g., [100,105]), and these theories account for processes of adaptation, learning, and decision making that are core properties of a complex adaptive system (e.g., [169]).

As separate components of the social system, individuals are the drivers of bottom-up processes, and the collective action driven by their cognition (Section 2.3). Empirical data have shown how varied individual responses are, and that these responses were largely rational and adaptive, albeit heavily influenced by social connections, identity, experience, norms, and roles. Just as the individual system influences the physical and social systems, past experience and the current context of the physical and social systems shape decision making in the individual systems [188,198]). The social system has been found to be a significant factor in what decisions are made and how well individuals survive disasters (e.g., [121,190,191]). Recent research leverages cognitive science approaches that utilize decision-making theory to explain individual behavior as shaped by complex interacting variables including the environmental context, emotions, experience, social norms, and identity (e.g., [192,196]), a source of complexity within the overall system.

3.2. Integrating the Physical, Social, and Individual Systems

Within physical, social, and individual systems, such as cities, the properties and dynamics of a complex adaptive system are evident in the sense that interactions between individual elements lead to emergent behavioral patterns and adaptation, and heterogeneity is present in disaster impacts, collective behavior, and individual experience. The webs of connections, relationships, and interactions within the systems lead to adaptations as system elements learn and respond to new experiences. More significant, the system effects in the physical system affect both individuals and society; societal dynamics impact both the physical and individual systems; and individual actors affect their physical and social systems. The dynamics in these three interacting systems as hypothesized could create their own sets of adaptations and emergent behaviors; however, disaster research studies tend to be focused on one particular subset of human behavior in the systems rather than on how the interactions between systems create feedback and aggregate effects and complexity.

To account for these greater systems interactions, we propose a framework with three intersecting systems within a complex adaptive system: the physical, social, and the individual systems, as shown in Figure 1. Interactions between the physical, social, and individual complex adaptive systems aggregate to create larger effects from their properties and dynamics. Heterogeneity can be found in the variations of disaster impacts on populations and geography. Flows exist with the migration of populations, individuals sharing information, the physical force of the disaster, and subsystems interacting. For example, when significant rainfall leads to river flooding, charitable organizations cooperate with federal agencies, and individuals self-organize and apply occupational skills to save neighbors. In a disaster, all three systems are thrown out of equilibrium and go through periods of adjustment to return to some form of stability. The return to equilibrium internal to each system and externally between systems is accomplished in processes of emergence and adaptation.

At the center of a complex adaptive system are the heterogeneous actors interacting in processes that create feedback, shifting the system in and out of equilibrium at some tipping point or critical threshold when a smaller change triggers a set of unstoppable processes such as bank runs [203]. In disasters, the tipping point is when conditions have built up to a point at which society is seriously harmed and can no longer operate its essential functions. The time of impact is an example of the tipping point for a tornado, whereas the point at which a river crests over its levee would be the tipping point for a slow-onset flooding disaster. These tipping points occur when the positive and negative feedback in the system are out of balance. In the case of a natural disaster such as a wildfire, they can occur when positive feedback (adding energy into the system and amplifying change) in the form of dry, hot air is not balanced with weather systems bringing negative feedback (removing energy from the system and decreasing change) in the form of rain moving into the area. A nuclear power plant accident also provides an example of feedback in a human-made disaster. For example, cutbacks in funding for well-trained, qualified technicians could create positive feedback that leads to a failure to identify minor operating problems and implement the appropriate safety protocols. Numerous sources of feedback can be found operating in any particular disaster and can be the root cause of cascading disasters [113], adding to the complexity of the system and creating both added risk and opportunities for mitigation.

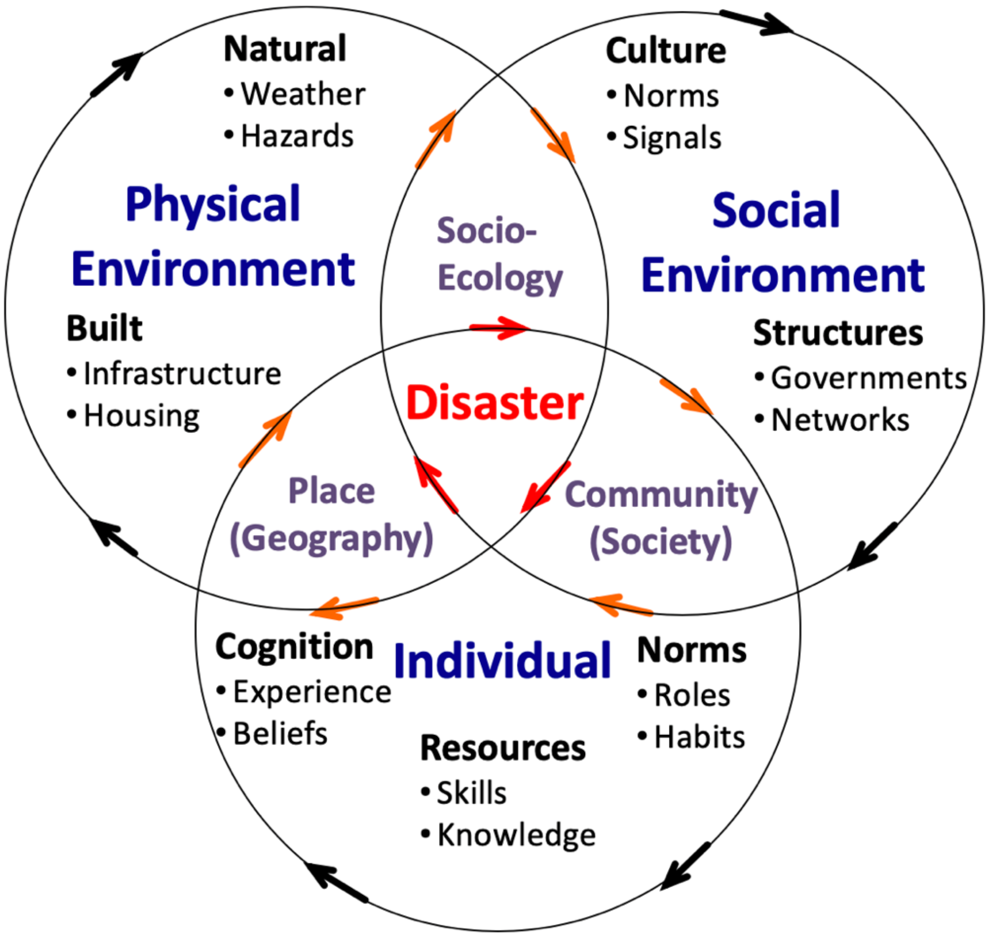

Figure 1. Framework for understanding the intersecting complex adaptive systems of disaster.

A complex adaptive system's internal interactions that lead to emergence, adaptation, and disasters are evident in many real-world examples. For instance, volcanoes provide an example of how physical forces build up pressure inside the earth until they reach a critical threshold and are released in an eruption. From the physical system, discussed in Section 2.1, we can observe how a greater frequency of volcanic eruptions creates a negative feedback signal that signals settlements to move farther from the volcano and away from hazards. The fertility of volcanic soil creates positive feedback motivating people to settle closer to the volcano, thus increasing the hazard. The negative and positive feedback lead to settlement patterns such as found by Small and Naumann [204]. In this scenario, past individual experiences of volcanic eruptions and livelihoods, such as taking care of livestock, also influence how people understand and respond to these events, creating variations in the perceptions of the hazard and evacuation rates [205,206]. Cultural and social factors create social forces and norms that affect how communities organize and communicate to prepare, mitigate, and respond to volcanic eruptions [207], and complexity theory suggests these forces can be identified and measured to find patterns in system behavior.

In the social system (Section 2.2), forces that affect flooding include structures built by governments and landowners, building codes, and flood management policies in the form of regulation, insurance, and land management policies implemented to reduce the risk and costs of flooding (e.g., [208–210]). The adjustments between the physical (Section 2.1) and social systems (Section 2.2) create cycles of flooding and implementation of new flood protections [211]. These interactions reduce the frequency of flooding events, but also increase the risk of catastrophic floods if flood protection measures fail [212]. As theorized in the Panarchy model [88] and complex adaptive system theory in complexity science [18], flows in the two complex adaptive systems, the physical and social, are continuously interacting and readjusting. The feedback between flows ultimately leads to a tipping point or critical threshold, when the systems are thrown out of equilibrium and catastrophic flooding.

The individual system, discussed in Section 2.3, also creates forces that lead to feedback between complex adaptive systems. They form from bottom-up processes such as when public opinion builds to a point of revolution or when an individual in technological systems triggers extreme damage through human error or implementation of weapons of mass destruction such as planes or bombs. The Exxon Valdez oil spill provides one such example of the impact of individual actors interacting with physical and social systems. At the disaster's tipping point, the Exxon Valdez tanker grounded on Bligh Reef in Prince William Sound due to multiple factors [213]. The ship's master (captain) and the third mate played individual roles with errors in judgment related to alcohol, fatigue, and work overload. Expanding out from the individual to the social system, the Exxon Shipping Company was found to have inadequate manning procedures, insufficient chemical dependency monitoring programs, and to have manipulated shipboard reporting of crew overtime. Preventative and mitigation measures in the form of regulations, equipment, and response plans to guard against the environmental risk and respond to oil spills were determined to be inadequate relative to the scale of the oil spill [213–215]. In the aftermath, post-disaster clean-up and litigation efforts were just as harmful as the oil spill itself [216,217], continuing environmental and societal damage long after the disaster [218]. Further complicating system action and adaptation, perceptions of the incident were manipulated in media coverage [219,220]. In these cases of high-impact, low-probability events, the complexity of complex adaptive system dynamics as well as society's acceptance of often poorly understood risks makes such technological disasters inevitable.

The analysis of disasters from the perspective of complex adaptive systems provides insight into the forces that shape and lead to disaster as discussed here and in Section 3.1. By identifying the connections between the physical, social, and individual systems and examining their relationships, researchers can measure the flows that push complex adaptive systems in and out of equilibrium. In the case of volcanic eruptions, equilibrium is established from long-term flows that lead to a balance of population size relative to the distance from the volcano. Changes in flooding hazards show how the social system continuously adapts with the physical system, reshaping flood plains. Analysis of feedback within the social system involved in the Exxon Valdez oil spill shows that the positive feedback from economic and social forces were not balanced with corresponding negative feedback. The oil spill was an inevitable outcome of a social system out of equilibrium, creating positive feedback that tipped over into the physical system and throwing it also out of balance. For disasters, the lens of complex adaptive systems provides new avenues for exploring causation and identifying forces and solutions that can lead to negative feedback and maintain equilibrium between systems.

3.3. Applications and Implications of Complex Adaptive Systems

Beyond the fundamental analysis of feedback and system equilibrium, the application of complexity science to disasters has a number of implications for disaster research and more generally towards more sustainable and resilient cities. Theories of self-organization, emergence, and interacting processes are central to both complexity and disaster, and these properties, as understood in complex adaptive systems, are already being applied in some areas, such as with the model of the adaptive cycle in Panarchy [88]. More important, the properties highlighted in this review—heterogeneity, webs of connections, relationships and interactions, and adaptations arising from individual actions, decisions, and learning—give rise to nonlinear dynamics and high levels of uncertainty. The nonlinear dynamics indicate the potential presence of power laws and, thus, proportional relative changes in the system that vary as a power of some attribute. Power laws are absent of any "average," and events in the systems described by power laws occur as "many small ones, a few larger ones, and occasionally extremely large ones" [221]. The negative and positive feedback often made visible in data distributed by power laws are continuously driving the system into a critical phase [222], functioning at ever greater efficiencies and toward the edge of chaos as described in Kauffman [41] and Lansing [36].

In complexity theory, the feedback created by multiple interacting subsystems creates observable patterns as the system shifts in and out of equilibrium. One example of these patterns is the self-similarity evident in the social organizations represented by networks. Self-similarity occurs when one part of an object displays the same pattern as its whole, such as the leaves of a fern. Fractals are self-similar geometric objects or patterns, and by applying analysis to identify these patterns, fractal network researchers have found network patterns to be a function of natural optimization processes [223–225] such as those in cities. Family groups self-organize themselves into nested hierarchies and social systems proportionally sized in relation to available flows of food, material resources, and other cultural information [224]. Another societal pattern can be found in urban growth. As societal cultures change, the rates of innovation, their wealth creation, patterns of consumption, and behavior follow scaling relationships [226]. The measurement of these relationships maps behavioral patterns or signatures in one set of cities that could serve as indicators or patterns of properties in others. Signatures are the distinctive characteristic patterns that can signal the presence of particular variables or interactions. Family network structures and urban growth both illustrate how the dynamics of a complex adaptive system create patterns with the potential for short-term prediction of self-organization and optimized scaling.

The complexity of the systems and their nonlinear dynamics preclude the possibility of traditional event prediction. Unlike classical Newton approximations that produce a single-point solution, such as point estimates of parameters in linear regression, a complex adaptive system cannot be approximated with linear equations for long. Instead, researchers and practitioners must look for a variety and range of bounded solutions. These systems are also sensitive to initial conditions as described in Lorenz's [227] "butterfly effect". As complex adaptive systems, we can expect that the pre-existing conditions of the physical and social systems will have significant effect on how well social systems prepare for, respond to, and recover from disasters, and this sensitivity to initial conditions will prevent reliable event prediction. However, although more research is needed, there is evidence from simple models of complex systems that early-warning signals could be detected in systems' behavioral patterns before some tipping point and a shift in the system occurs [228]. Just as patterns in weather systems can provide short-term predictability, patterns in disasters could be bounded in probabilistic outcomes. Practitioners will not find final solutions or policies for disaster preparation, response, and recovery; rather, changes in behavior and policy could mitigate some harmful effects while preventing others. The effectiveness of policies or disaster risk management plans will vary over multiple events and hazards, which in today's urban environments are increasingly cascading hazards [2], and will require adjustments given existing conditions. Modelers will need to create simulations that represent the probabilities of intervention strategies [229,230], and researchers will need to develop both simple and complex models that specifically study the mechanisms and feedback relevant in disasters (e.g., [231,232]). The goal of scientific study in this area will require a shift from requiring definitive prediction to determining probable outcomes.

Understanding the dynamics of a complex adaptive system requires the exploration of the latent capabilities and vulnerabilities in the particular system; i.e., those unobservable variables that are found to be significant in disaster outcomes as a result of bottom-up and feedback processes [81,233–235]. These processes can be partially attributed to the self-organization that occurs as individuals and organizations exploit existing assets or weaknesses. Existing techniques to analyze latent variables include those from statistics (e.g., Regression Analysis, Latent Dirichlet Allocation), machine learning (e.g., Latent Semantic Analysis, Factor Analysis, Hidden Markov Models), and the tangential field of network analysis such as the measurement of social network capacity. The application of these and other innovative statistical and machine learning techniques for latent variable analysis tailored for disaster could improve research and practice in disaster management (e.g., [236]).

Researchers and practitioners continue to contend with the multitude of interacting variables and adaptations in the physical (Section 2.1), social (Section 2.2), and individual (Section 2.3) systems, and conceptual models of complex adaptive systems such as discussed in this paper (Section 3.2) are needed to study and test these interactions in these system of systems. Research in the area of complex adaptive systems must explore the multiple interactions of system components explained by multiple theories and visible in nonlinear dynamics that cannot be studied using traditional qualitative and mathematical models [20]. Social network analysis and geographical information systems and other computational methods in the expanding field of computational social science provide new forms of data that can more precisely measure the processes in physical, social, and individual complex adaptive systems (e.g., [237–239]). Techniques in the computational social sciences using power law analysis and agent-based models are necessary for the analysis of systems that cannot be reduced to single elements, actors, or processes (such as those found in cities). In experimentation with complex adaptive systems, computer simulations provide the necessary tools to magnify small differences, making them observable (e.g., [240,241]). They also enable collaborative processes that develop shared-risk models for community stakeholders and policy-makers (e.g., [4,242–245]), transforming data into information and then knowledge. Analysis of complex adaptive systems in disaster requires a different approach and new methodological tools that can manage large, heterogeneous datasets; identify and calculate power laws; run the high sample sizes of events in simulations needed to generate a range of expected outcomes; simulate events and implement theories that cannot be tested with available field data; identify and explore dynamics with multi-level dependencies; and apply machine learning and other computational techniques for latent variable analysis.

The implications discussed above and corresponding suggestions for methodological approaches are not intended as a comprehensive set of approaches and techniques to address the disaster research questions; rather, they suggest potential areas for exploration. Dynamics in complex adaptive systems produce detectable patterns and potential signatures for particular interactions, and although problems in complex adaptive systems do not produce optimal, single-point solutions, possible outcomes can be computed. The lens of complex adaptive systems presents a new paradigm for disasters that leads to new lines of inquiry. What data are necessary to observe and measure the key feedback processes present in disaster? What are the repeatable patterns observed in disasters? Are there consequential differences between the complex adaptive systems of urban versus rural regions? How should computer models of a complex adaptive system in disaster be designed to improve understanding of system interactions? Further work is necessary to establish whether complex adaptive systems can provide a useful level of prediction, as was the case in weather forecast modeling. However, the process of studying disasters from the perspective of theories of complexity can provide insight into the interactions of individual, social, and physical systems behavior.

4. Summary

As more and more people are living in cities and the threat of disasters is ever growing, it is important to explore not only cities through the lens of complex adaptive systems but also disasters. While it is often noted that cities are often far from equilibrium (e.g., [20]), disasters are the inflection points at which cities and communities move from a steady state to one of instability with the potential of significant loss and harm. A century of research on disasters has evolved from the study of single discrete events that were largely addressed with top-down responses for emergency rescue and management to the study of continuous, repetitive events with complex interactions between systems and across scales from cities to communities. Originally these discrete events were not seen as interacting systems or as a system of systems; however, this has changed over the last few decades. To demonstrate this development, we have reviewed and organised theories for disasters as three complex adaptive systems, the physical (Section 2.1), social (Section 2.2), and individual (Section 2.3). Furthermore, we showed that these systems are interconnected (Section 3.1) and described how these systems are integrated through webs of connections and characterized by all the traits of complex adaptive systems (i.e., heterogeneity, interacting subsystems, emergence, adaptation, and learning as discussed in our introduction (Section 1)). The lens of complex adaptive systems enabled us to introduce a new conceptual framework of physical, social, and individual systems that interact across scales (Section 3.2). This conceptualization lays down a foundation for disaster science that explicitly studies disaster events as parts of ongoing interactions and processes of subsystems rather than addressing them as individual systems. The recognition that disasters arise within complex adaptive systems offers us a deeper understanding of these events and the theories and tools available in complexity science as applied in Section 3.3.

As evident in this paper, explicit study of the interactions between these three systems is standard in today's literature (Sections 3 and 3.1). However, further exploration of their feedback is needed to improve understanding of the nonlinear dynamics that dominate disaster phenomena producing the complexity of the overall systems (Section 3.3). The major contribution of this paper is a framework (Section 3.2) that can be used as a conceptual device to integrate disaster theories into urban planning and and disaster risk management. The framework accounts for the complex nature of cities and disasters and balances the interacting dynamics of multiple subsystems, the understanding of which are necessary to develop policies for promoting resilience and sustainability within cities and broader urban systems. The framework does not invalidate older theories; rather, it creates a space for these theories to intersect and interact, providing stronger explanation for human and environment behavior. It also furthers the conception of complex adaptive systems in disasters and underscores its relevance by directly recognizing and addressing the inherent complexity of disasters. With this perspective, researchers can better take advantage of available computational techniques for studying complexity and more fully explore the dynamics that take place at the intersections of the physical, social, and individual systems such as those that cities encompass.

Author Contributions: A.B. and A.C. developed the topic, and A.B. prepared the initial draft; A.C., A.B. and W.G.K. prepared the final draft for submission and all authors approved its content. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially supported in part by the Defense Technology Research Agency (DTRA) under Grant number HDTRA1-16-0043 and the Center for Social Complexity at George Mason University. The opinions, findings, and conclusions or recommendations expressed in this work are those of the authors and do not necessarily reflect the views of the sponsors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank the two anonymous reviewers for providing constructive feedback on previous versions of this paper.

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

Abbreviations

The following abbreviations are used in this manuscript:

CAS	Complex Adaptive Systems
CHASMS	Cascading Hazards to disAsters that are Socially constructed eMerging out of Social vulnerability
COR	Conservation of Resources
DROP	Disaster Resilience of Place
DMC	Decision-Making Capacity

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