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A Narrative Literature Review of the 2011 Joplin, Missouri Tornado: Myriad Lessons Learned from One of the Worst Tornadoes in U.S. History

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Abstract: We examined the impacts and lessons learned from the 2011 Joplin, Missouri, tornado, one of the most devastating tornadoes in U.S. history. The review covers various aspects, including vulnerability and resilience, building codes, preparedness, risk communication, damage assessment, economic impacts, and response and recovery strategies. Key findings highlight the role of building codes and structural integrity in mitigating damage, the importance of effective communication and preparedness in enhancing community response, and the significant influence of socioeconomic factors on recovery processes. Studies on community resilience emphasize the necessity of integrated approaches that combine engineering, social, and economic perspectives. The review also underscores the value of empirical data from building permit records, spatial-temporal analyses, and economic models in understanding recovery trajectories. Contributions from interdisciplinary research provide insights into improving disaster preparedness, response strategies, and long-term resilience. The analysis offers valuable lessons for policymakers, emergency management officials, and urban planners, aiming to enhance resilience and reduce vulnerability to future tornadoes and other natural disasters. The review's findings suggest that proactive planning, robust building practices, and effective communication are crucial for fostering resilient communities capable of withstanding and recovering from severe weather events.

Keywords: Joplin Tornado; Tornadoes; Tornado Recovery; Community Recovery; Disaster Recovery

1. Introduction

On May 22, 2011, Joplin, Missouri, experienced one of the deadliest and most destructive tornadoes in U.S. history. The EF-5 tornado carved a path of devastation nearly a mile wide and over six miles long, resulting in 161 fatalities and injuring more than a thousand people. With winds exceeding 200 miles per hour, the tornado obliterated homes, businesses, and infrastructure, causing an estimated $2.8 billion in damage [1]. The sheer scale of destruction and the subsequent recovery efforts have provided a wealth of data and insights into disaster management, resilience, and community recovery. In this review, the authors summarize the extensive research conducted in the aftermath of the Joplin tornado. The tornado's impact on various facets of the community, including structural integrity, economic stability, and public health, has been extensively studied, offering valuable lessons for future disaster preparedness and response. The reviewers sought to highlight the elements that contributed to the vulnerabilities the tornado exposed and the resilience demonstrated by the community by examining the findings across multiple disciplines.

2. Materials and Methods

The first section focuses on vulnerability and resilience, exploring how different demographic and structural factors influenced the severity of the tornado's impact and the community's ability to recover. Researchers have shown that building codes and construction practices played a significant role in determining the extent of damage, underscoring the need for robust and tornado-resilient building standards. The reviewers also examined the importance of preparedness, effective risk communication, and the public's response to warnings, which are pivotal in reducing casualties and enhancing immediate protective actions. Subsequent sections focus on the economic and social dimensions of the recovery process. The authors discuss the innovative methodologies used to assess the damage and economic losses, including applying advanced spatial-temporal analysis tools and economic modeling. Such approaches have provided an understanding of the long-term economic impacts and the effectiveness of various recovery strategies. The role of community resilience, particularly the contributions of local businesses and social networks, is examined to understand how grassroots efforts facilitated a faster and more cohesive recovery. Lessons from the 2011 Joplin tornado offer insights for enhancing disaster preparedness, response, and recovery in other regions prone to severe weather events. The review highlights the importance of integrating engineering, social, and economic perspectives to build resilient communities.

3. Results

3.1. Vulnerability and Resilience

Egnew et al. (2018) sought to quantify the vulnerability of residential structures to extreme wind hazards, including tornadoes, by examining the relationship between observed physical damage levels and standard building attributes [2]. They investigated data from 2,076 single-family residential structures affected by the 2011 Joplin tornado. Egnew et al. developed a model using multinomial logistic regression, revealing that houses showed an increased likelihood of higher tornado damage levels for newer houses, houses with lower value per unit living area, and year built, living area, and number of stories weakly positively correlated with damage level likelihood [2]. Houston et al. (2017) conducted a telephone survey following the Joplin tornado to explore resident perceptions of community resilience (CR) [3]. The researchers found that participants expressed generally positive perceptions of their community's resilience after the disaster; however, age differences largely shaped those perceptions—older participants were more likely to plunge into higher CR perceptions. Those with more direct tornado experiences held lower CR perceptions. Participants engaging in traditional media and interpersonal communication (e.g., friends, family, and neighbors) were likelier to have higher CR perceptions. Egnew et al.'s findings stressed the importance of mediated and interpersonal communication in fostering resilience after a major disaster [2].

Langan et al. (2017) probed the inordinate age-associated changes in the levels of resilience as survivors rated their psychological approach to life three years after the violent EF5 Joplin tornado [4]. The young, middle-aged, and older adult participants responded to self-rated resilience items, and most of them reported normal to high resiliency with a minority of difficulty in the adjustment of the impact of the disaster, findings in which age was not a significant influence. Wang et al. (2022) modeled the effects of different levels of retrofitted wood-frame residential building characteristics to reduce the vulnerability to violent tornado impacts on households and the subsequent community social and economic disruption at three-time points over 72 months [5]. Wang et al. detailed a method to select representative residential building performance levels from those of non-suggested retrofit to that of new design code adoption and then apply the selections to simulate a 200-mile-per-hour (mph) violent tornado model was erected and auto-assigned a community resilience metric to assure economic and population stability and dislocation prediction [5]. Wang et al. tested their approach in Joplin, Missouri, and illustrated the significance of community resilience meet, as based on home retrofit and new design code levels [5].

Wang and van de Lindt (2021) present a method designed to elucidate the community recovery process following disasters, with a focus on the impact of dynamic post-disaster decisions and policies [6]. Employing a multilayer Monte Carlo simulation model, the researchers depicted a two-stage recovery process for residential buildings: functional downtime due to delays and functional downtime due to repairs. Adapted from the REDI framework, the delay component incorporates various factors that impede repairs, including post-disaster inspections, insurance claims, and building permits. The authors assessed household income levels to estimate financing delays, consid-

ering the availability of different funding resources such as insurance and loans. The repair component leveraged the FEMA P-58 approach, originally developed for post-earthquake analysis, and controlled by fragility functions. An illustrative example using the 2011 Joplin tornado demonstrates the model's capability to simulate residential recovery as a time-stepping process, allowing for the evaluation of both pre-disaster mitigation and post-disaster policy implementations. Findings showed the role of delay time in the recovery process, revealing that it dominated the recovery timeline for typical buildings in the EF5 region of the simulated Joplin tornado, with mean delay times accounting for 64.4% of the total recovery period. The proposed policy cases varied in their impact on the delay process; for example, building retrofits significantly reduced repair times, expediting the recovery process by 1.7 times. Comprehensive implementation of all proposed policies and mitigation strategies accelerated recovery by 2.4 times. Wang and van de Lindt's findings highlighted the substantial improvements in the percentage of buildings achieving full recovery over different time frames, particularly under the most comprehensive policy scenario [6].

Wang et al. (2021) used a fully quantitative model to examine the repercussions of tornado-induced damage on physical infrastructure—specifically buildings and electrical power networks—and its subsequent effects on the local population and economy [7]. The study measures outcomes using a range of resilience metrics, which often encompass socioeconomic characteristics such as the number of injured individuals and households or businesses without essential services like water. The authors presented an illustrative case study of the 2011 Joplin tornado using the new open-source Interdependent Networked Community Resilience Modeling Environment (IN-CORE). The IN-CORE environment integrates a computable general equilibrium (CGE) economic model to evaluate household income, employment, and domestic supply dynamics before and after the tornado. The model also incorporates detailed demographic data assigned to each structure, enabling the calculation of resilience metrics related to population dislocation impacts from the tornado. Three distinct retrofit strategies for residential buildings can enhance community resilience. The research quantifies the effectiveness of these strategies on physical, economic, and social sectors by computing relevant metrics. The results demonstrate logical trends in building damage estimation and highlight the significant contributions of retrofit strategies in mitigating tornado impacts. The substantial contribution of this study lies in its ability to quantify, for the first time, the effects of retrofit strategies for tornado loading in terms of their impact on socioeconomic metrics. Such a novel approach provides insights into how retrofit interventions can enhance community resilience by reducing physical damage and mitigating adverse socioeconomic outcomes.

Abdelhady et al. (2023) expanded on the quantitative frameworks initially popularized by Wang and van de Lindt (2021) and Wang et al. (2021), applying similar methodologies to a broader spectrum of hazards [6–8]. Abdelhady et al. emphasized the importance of adaptable frameworks focused on a single type of natural disaster and providing the flexibility to assess and mitigate risks from multiple hazards [8]. While Wang and van de Lindt provided a quantitative assessment of tornado resilience, the subsequent adaptation and broadening of their framework by Abdelhady et al. suggested a shift towards more versatile and inclusive models [6, 8]. Such models are increasingly important in researchers' and practitioners' understanding of resilience, as models allow communities to better prepare for and mitigate the impact of threats. The progression from a focused model to more generalized frameworks illustrated the dynamic nature of resilience research, stressing an ongoing trend toward improving disaster preparedness through innovative assessment tools.

3.2. Building Codes

As Smith et al. (2012) demonstrated, engineering solutions alone cannot ensure facilities perform as desired during tornado events [9]. Smith et al. examined the impact of 2011 tornadoes on facilities (e.g., hospitals and emergency operation centers). The researchers used the lessons learned to develop tornado recovery advisories to enhance these facilities' performance and ensure the building occupants' safety. Similarly, Coulbourne and Miller (2012) offered insights into the structural integrity of educational facilities [10]. Their findings indicated that vulnerabilities were not limited to older schools but also found in newer schools in Joplin, with a conclusion suggesting that building codes and construction practices should receive additional attention. Dao et al. (2014) investigated damage patterns in residential structures, arguing that the location and orientation of the structure relative to the tornado track could influence the scale of damage—this could potentially inform future building codes and guidelines [11].

Prevatt, Coulbourne, et al. (2012) investigated the structural damage resulting from the Joplin tornado [12]. Through a detailed survey of the affected area, the researchers assessed the performance of various building types under extreme wind loads. Findings indicated a widespread failure in roofing systems, which often precipitated subsequent structural failures within residential and commercial buildings. The analysis highlighted deficiencies in the existing building codes, which could not adequately protect structures from the intense loads imposed by such high-magnitude tornadoes. The case for implementing tornado-resilient building codes was grounded in the data collected, which demonstrated the inadequacy of current standards to ensure the integrity and safety of buildings subject to tornado-induced stresses. The study's implications are significant, emphasizing the need to change building design practices, particularly in tornado-prone regions.

Prevatt, van de Lindt, et al. (2012) examined structural failures observed during the 2011 tornado outbreaks in the United States, including Joplin, which accounted for economic losses surpassing $25 billion [13]. Prevatt, van de Lindt, et al. argued that impact assessments must also consider long-term and broader implications, such as social disruption and psychological effects on communities [13]. The researchers indicated that the extent of damage incurred could link to the evolution of building codes and construction practices that failed to account for such severe weather events. Prevatt et al. suggested a multidisciplinary approach incorporating engineering research with social and economic studies to advance a more resilient future against tornadoes [13]. The practitioner's goals should foster a new design paradigm that results in building code changes and social practices to improve community resistance and mitigate future losses from tornadoes. Prevatt et al.'s assessment stresses the urgency for transformative change in building design and construction practices, especially in regions susceptible to tornadoes.

Prevatt et al. (2012) provided an in-depth analysis of the structural damage observed in the aftermath of significant tornado events in Tuscaloosa, Alabama, and Joplin, Missouri, drawing upon the findings to advocate for enhanced construction practices and structural retrofits aimed at increasing resilience to such disasters [14]. The researchers examined damage patterns, assessment techniques, and the subsequent recommendations for improvements in building practices. The Enhanced Fujita (EF) Scale is at the core of the discussion. Prevatt et al. emphasized the relationship between construction quality and the extent of damage incurred by buildings. Structures incorporating robust construction techniques, including better anchoring and stronger connections, demonstrated greater resilience against tornado forces—an observation leading to a broader discussion on the need for improved construction practices [14]. Specifically, the authors advocated reinforcing vertical load paths and applying structural sheathing panels on walls to enhance structural integrity.

Roueche and Prevatt (2013) analyzed residential damage caused by the 2011 tornadoes in Tuscaloosa, Alabama, and Joplin, Missouri [15]. The research team's assessment was rooted in data collected from homes impacted by the tornadoes. The authors applied the EF Scale to rate the damage and integrated information such as the age of the homes, the construction materials, and the home size into their analysis. Roueche and Prevatt indicated distinct patterns of structural failure that were directly related to the tornadoes' intensity and trajectory and the quality of construction. The most significant damage was observed in non-engineered residential properties, revealing a substantial weakness in typical construction methods against such powerful storms. The researcher's findings are important for developing construction practices and building codes that protect residential structures from tornado-induced damage. Roueche and Prevatt formulated a strong case for developing tornado-resilient building designs and construction standards by documenting and analyzing the specific damage patterns during these tornadoes. Their work contributed to the ongoing conversation about how best to ensure the safety and integrity of residential buildings in the face of increasingly frequent and severe weather events.

3.3. Preparedness, Risk, and Warnings

Paul et al. (2014) explored various predictors that influenced how residents of Joplin responded to tornado warnings before the EF-5 tornado [16]. One key finding was that individuals with previous experiences of tornadoes were more likely to heed the warnings and take appropriate protective actions. Joplin residents who received clear, detailed warnings were more likely to take immediate and effective action, such as seeking shelter in a safe location. Paul et al. also highlighted the importance of social networks and community ties in disaster response [16]. Individuals who received warnings from multiple sources, including family, friends, and official channels, were more likely to respond appropriately. Paul et al.'s findings stressed the need for integrated communication strategies leveraging various channels to disseminate warnings effectively [16]. Another significant predictor was the perceived

severity of the threat. Residents who believed the tornado posed a serious risk were more likely to take protective measures—a perception influenced by the content and tone of the warnings and the credibility of the sources issuing them. The researchers also identified barriers to effective response, such as complacency and fatalism. Some residents did not take the warnings seriously because they believed they were not at risk or that there was little they could do to protect themselves, highlighting the need for ongoing public education campaigns to increase awareness of tornado risks and the importance of taking warnings seriously. The researchers provided valuable insights into the factors influencing public response to tornado warnings, emphasizing the need for clear, specific, and credible warnings and the importance of leveraging social networks and multiple communication channels to reach the public [16].

Paul and Stimers (2015) examined the behavioral determinants influencing compliance with tornado warnings during the Joplin, exploring the factors governing individuals' response to warnings [17]. The researchers conducted a field study employing a cross-sectional survey, canvassing a diverse Joplin population segment. Research team members gathered data regarding the residents' adherence to the tornado warnings issued during the calamity. Paul and Stimers focused on several potential influencers of compliance, including (a) the multiplicity of warning sources available to individuals, (b) whether the respondents were at home during the tornado's onslaught, (c) their historical encounters with tornadoes, and (d) gender-based differences in responding to the warnings [17]. Employing multivariate logistic regression, the authors identified these factors as statistically significant predictors of compliance, providing an understanding of the behavioral dynamics at play—results revealed several key findings. Individuals with access to multiple warning sources were likelier to heed the warnings, stressing the role of a multi-channel communication strategy in ensuring widespread compliance during emergencies. Data analysis indicated that those at home when the tornado entered the community were more likely to take protective action, pointing to the necessity of a pervasive alert system capable of reaching individuals regardless of location. Previous experiences with less severe tornadoes tended to breed complacency, resulting in lower compliance rates, suggesting that personal history with tornadoes can obfuscate risk perception and diminish the urgency of response in situations. Paul and Stimers also highlighted a gender disparity in responses, with women more likely to seek shelter upon receiving tornado warnings than men [17]. Policymakers and emergency management officials can tailor more effective preparedness and response strategies by pinpointing the elements influencing warning compliance, particularly in regions prone to severe weather events like tornadoes.

Kuligowski and Kimball (2018) authored a National Institute Standards and Technology (NIST) Technical Note 2008 [18]. They developed a guide in response to the need for widely accepted standards for emergency communications in tornado events. The authors particularly addressed creating and providing public alerts, focusing on outdoor siren systems and short message service (SMS) platforms, aiming to standardize emergency communication policies and procedures at various levels, potentially including local, state, and national jurisdictions. The researchers detailed guidance for communities on crafting and delivering public alerts for imminent threats, employing a framework known as the protective action decision model (PADM). The PADM outlines pre-decisional processes (receipt, attention, and comprehension) and decisional processes (credibility assessment and risk personalization). For outdoor siren system alerting, the guidance suggests reaching a wider audience, enhancing comprehension, boosting credibility and risk personalization by employing push technology to disseminate audible alerts, and engaging with leaders of vulnerable populations. The authors also recommended standardizing siren tones and meanings across communities to minimize public confusion and trust issues [18]. Casteel (2018) noted the standardized tone suggestions [19]; they stated:

"The service assessments conducted by the NWS after the Joplin tornado made a rather bold suggestion: that the NWS go beyond the warning process and attempt to communicate the impact of severe weather by providing more specificity of potential outcomes. The National Institute of Standards and Technology's final report on the Joplin tornado also noted the need to change to a more impact-driven warning process" [20] (p. 11).

Regarding short message alerting, Kuligowski and Kimball (2018) advocated using push technology and opt-out platforms to increase the receipt and attention of messages, suggesting clear, direct language with information about the source, hazard, location, timing, and recommended actions to enhance message comprehension [18]. Kuligowski and Kimball also advised on the style of messages to increase perceived threat credibility and personalization, emphasizing the seriousness and consequences of the event, along with clear action instructions. Lastly, the authors identified unanswered research questions and potential future guidance areas, such as alerting frequency,

effectiveness of message testing, reaching vulnerable populations, and best practices for public educational campaigns on public alerting. Kuligowski and Kimball's Technical Note represents a significant effort toward improving public safety and response efficiency in emergencies by providing a structured and researched approach to public alerting systems [18].

Luo et al. (2015) conducted a telephone survey 2012 targeting residents in Tuscaloosa and Joplin to ascertain the correlation between the number of warning information sources (WISs) and the likelihood of individuals taking protective action during tornado events [21]. With a working sample of 782 respondents, the researchers employed logistic regression analysis to interpret the data. Luo et al.'s design allowed them to adjust for confounding variables and more accurately determine the impact of multiple WISs on protective actions [21]. Results indicated a significant increase in protective actions among Joplin residents who accessed two or more WISs compared to those with only one source. However, the pattern was not mirrored in Tuscaloosa, suggesting regional differences in how WISs influence behavior. Across both cities, an emergency plan consistently elevated the likelihood of taking protective action. Luo et al. also found racial and marital status disparities in responses to tornado warnings [21]. Results revealed valuable insights for emergency management agencies and public health officials. In areas like Joplin, the benefit of multiple WISs becomes apparent. The researchers advocated prioritizing the enhancement of WISs in such locations and among populations with lower awareness or increased risk of not receiving warnings. Based on the findings, Luo et al. recommended that policymakers consider the number of WISs as a crucial metric for evaluating access to warnings and the probability of receiving any warning [21]. The researchers concluded that a multi-pronged approach to disseminating tornado warnings may significantly impact community response and protective action during disasters. They suggested that policymakers consider these findings when formulating disaster preparedness and response strategies, aiming to ensure that warnings reach as broad an audience as possible, especially in less-prepared or higher-risk areas.

Kuligowski (2020) revealed that many residents did not initially seek shelter due to a combination of factors, including a lack of immediate physical cues indicating the storm's severity [22]. Many survivors reported that their previous experiences with non-destructive tornadoes led to complacency, which compounded by emergency communications that often proved confusing or contradictory, leading to delayed responses until the tornado was unmistakably imminent. Kuligowski highlighted a conceptual model developed from survivor interviews that elucidates these patterns in decision-making and shelter-seeking behaviors [22]. She discussed how the aftermath of the disaster saw efforts to translate theoretical research into practical applications. Kuligowski's study on the Joplin tornado offered insights into human behavior in response to natural disasters, stressing the necessity of understanding the psychological and contextual factors that influence decision-making processes during emergencies. The researcher's findings advocate for significant improvements in how experts formulate and communicate warnings, suggesting a tailored approach that considers historical experiences with disasters, the message's clarity, and the communication channels' directness [22].

Through a phone survey in Tuscaloosa, Alabama, and Joplin, Missouri, cities heavily impacted by tornadoes in 2011, Cong et al. (2014) concluded that having an emergency preparedness plan was the strongest predictor for taking shelter during tornadoes [23]. They underscored the importance of family emergency planning in mitigating risks associated with rapid-onset disasters like tornadoes. Cong et al. (2017) analyzed the factors determining the number of information sources people used for tornado warnings in Tuscaloosa and Joplin [24]. They found that older age and having an emergency plan were predictors of using multiple sources. Cong et al. (2017) also discovered that educational level, marital status, and gender influenced how warnings were received [24]. The researchers concluded that emergency management should prioritize these demographic factors when disseminating tornado warnings to ensure broad and effective reach. Cong et al. (2021) investigated the effectiveness of pre-existing household emergency plans during the 2011 EF5 Joplin and EF4 Tuscaloosa tornadoes, especially whether discussions within families enhanced the utility of these plans [25]. The telephone survey of 1,006 respondents found that family discussions improved the plan's effectiveness, particularly in Joplin, where less frequent tornado occurrences had led to lower preparedness levels than in Tuscaloosa. Cong et al. (2021) supported the importance of involving family members in emergency planning, highlighting a proactive approach in disaster-prone areas that may need more experience or preparation for such events [25].

3.4. Damage and Economic Assessment

Researchers who have examined tornado impacts have produced a myriad of innovations in the field of disaster management and risk assessment. Peng et al. (2016) developed an in-depth framework for assessing tornado damage in low-rise non-engineered residential buildings [26]. The authors' model incorporates a translating tornado vortex model, calculations for tornado-induced wind loads, and a model for wind-borne debris impacts; it also includes a time-variant model for changes in internal pressure within structures. The framework produced a percentage damage index for individual components and an overall building damage ratio. As demonstrated by data from the Joplin tornado, the model performed with a high degree of accuracy. However, one must question the universality of a developed model to consider low-rise, non-engineered structures. Due to the nature of the model that was created by capturing the response of a system to one event (Joplin), it is plausible that a different tornado with different characteristics could yield a radically different set of coefficients. As a natural extension of the work by Peng et al., researchers must develop damage assessment models that apply to other forms of architectural design and construction practices [26]. Such work could involve collecting and analyzing data from various tornado occurrences, demonstrating these models' generality and predictive accuracy. In addition to the indirect fatal improvements in damage models and construction practices, new advances in material science and construction techniques could refine these models and far more effective mitigation strategies.

Pilkington et al. (2020) developed an approach to estimate the economic losses caused by tornadoes, considering the structural damage and the contents within the buildings [27]. Using the devastating 2011 Joplin, Missouri, tornado as a case study, the researchers enhanced traditional methods by integrating FEMA's HAZUS equations for estimating losses inside buildings. Their findings were validated against the actual events of the Joplin tornado, showcasing the method's accuracy. They explored the impact of the tornado's path by simulating alternative scenarios where the tornado followed different tracks across the city. The novel approach revealed that commercial and non-residential buildings played a significant role in the overall financial impact of the tornado. Pilkington et al.'s (2020) methods offered valuable insights for urban planners and policymakers, presenting a new layer of complexity to disaster impact assessments and underscoring the importance of considering internal contents in economic loss evaluations [27].

Thomas et al. (2013b) employed their automated system in their analysis of the Joplin, Missouri, tornado to effectively delineate the damage's extent [28], showcasing their methodology's precision and efficiency—it highlighted the system's capability to process and analyze high-resolution images to identify and classify the levels of damage sustained by buildings and infrastructure. The approach streamlined the damage assessment process and offered a scalable method applicable to other disaster scenarios. The automated system developed by Thomas et al. (2013b) shifted towards more dynamic and responsive disaster management tools, leveraging technology to provide faster, more accurate assessments that could significantly aid recovery and rebuilding following major natural disasters [28]. Thomas et al. (2013a) employed their innovative automated damage classification system to evaluate the post-storm damage of low-rise building roofing systems in Joplin, Missouri, using high-resolution aerial imagery [29]. The researchers assessed the aftermath of the severe storms that hit Joplin, focusing on precisely identifying roofing damages, such as missing tiles, holes, and other structural compromises. Thomas et al. (2013a) pinpointed and categorized the damages inflicted on individual buildings by applying advanced image processing techniques and supervised classification algorithms [29]. The Joplin case study highlighted the efficacy of the proposed system in real-world scenarios, showcasing how such automated tools can significantly expedite the damage assessment process, thereby aiding in the quicker mobilization of recovery and rebuilding efforts. Thomas et al.'s (2013a, 2013b) targeted approach in Joplin validated the system's practical application and underscored its potential to enhance disaster response strategies across similar urban settings [28, 29].

Attary et al. (2018, 2020) used the interdependent networked community resilience computational environment (IN-CORE) developed at Colorado State University [30, 31]; the researchers simulated the tornado's effects on Joplin's physical and socioeconomic sectors. Attary et al. (2018) predicted the damage to Joplin buildings and infrastructure, providing a valuable benchmark against actual damage assessments conducted in the aftermath of the tornado [30]. The modeling effort validated the IN-CORE system's accuracy and demonstrated its potential as a practical tool for emergency responders and urban planners. Attary et al. (2020) focused on the resiliency of communities prone to natural hazards, particularly through risk-informed decision-making tools, specifically modeling

Joplin [31]. The IN-CORE environment aids researchers in exploring community resilience by integrating diverse scientific, engineering, and observational data. The researchers estimated the damage caused by the 2011 Joplin tornado and validated the IN-CORE system by hindcasting this real event and comparing the simulated damage to actual field reports. The approach provides community decision-makers with important information to effectively consider various mitigation and recovery strategies.

Attary et al. (2019) focused on the interdependencies between the electric power network (EPN) and residential structures, aiming to enhance community resilience through improved risk-informed decision-making tools [32]. Using a local electric power company dataset, the researchers began with a detailed assessment of the tornado's impact on Joplin's EPN. The dataset included information on the topology of the power network; it was combined with spatial wind speed models and component fragility analyses to evaluate the extent of damage to electric poles and other infrastructure components. Attary et al.'s methodology integrated these physical damages with a probabilistic model to estimate the likelihood of power loss across different parts of the community based on the severity of the tornado's path [32]. The researchers leveraged a weighted cellular automata (CA) technique to model the flow of electricity from substations through the network, highlighting how damages to specific components like substations and transmission lines influenced the broader network and service delivery. Attary et al.'s approach allowed the researchers to visualize and quantify the cascading effects of infrastructural damage on community service continuity and safety [32].

Karstens et al. (2013) presented a detailed investigation into the patterns of tornado-induced tree falls as evidence of the characteristics of tornadoes themselves [33]. The researchers used high-resolution aerial photographs to digitally record the directions of fallen trees in the aftermath of the Joplin and Tuscaloosa-Birmingham tornadoes. The researchers compared empirical observations with simulations from analytical vortex models to infer characteristics of the tornadoes' near-surface wind fields. Karstens et al. identified specific tree fall patterns that aligned with hypothesized behaviors of tornado wind fields, such as concentrated bands of fallen trees parallel to tornado paths, which suggested lateral inflows and flow acceleration due to local topography. The researchers discussed how tree fall patterns extend beyond the primary damage paths, potentially due to phenomena like rear-flank downdrafts (RFD), which can exacerbate the tornado's destructive power. The authors' use of Gumbel distributions for tree-falling wind speeds provides a methodological innovation in estimating the near-surface wind properties of tornadoes.

The literature addressing preparedness, risk perception, and warning compliance during tornado events reveals consistent patterns in behavioral response. However, the way messaging systems, historical experience, and demographic factors integrate into emergency protocols remains fragmented. Paul et al. (2014) and Paul and Stimers (2015) identified prior tornado experience, perceived threat severity, and access to multiple warning sources as primary influences on protective action [16, 17]. Both studies emphasized that belief in personal risk, rather than the objective danger level, determined response behavior. Assuming that more warning sources automatically lead to better outcomes may oversimplify the issue. Luo et al. (2015) found this effect in Joplin but not Tuscaloosa, suggesting that regional sociocultural factors and baseline preparedness levels shape how individuals interpret and act upon warnings [21]. Paul and Stimers introduced gender and location at the time of warning as further determinants but stopped short of analyzing how these findings could inform message tailoring across population groups [17].

Kuligowski and Kimball (2018) took a systems-level view, advocating standardized protocols using the Protective Action Decision Model (PADM) [18]. Their recommendations centered on uniform siren tones, message clarity, and leveraging push technologies. These prescriptions addressed a major gap in prior work, which often focused on recipient behavior without fully analyzing the messaging system. Kuligowski (2020) extended this contribution through qualitative analysis, showing that conflicting or vague alerts combined with survivor complacency delayed shelter-seeking [22]. While researchers such as Paul and Cong focused on the quantity of warning sources, Kuligowski revealed that message coherence and consistency may be more decisive. Cong et al. (2014) and Cong et al. (2017) highlighted the role of family emergency plans and demographic predictors in increasing compliance yet did not fully assess how these variables interact with message design or dissemination platforms [23, 29]. Cong et al. (2021) reinforced the value of in-family disaster discussions, especially in regions with lower prior tornado exposure [25]. However, across studies, few researchers addressed how messaging systems could be customized to target vulnerable populations with limited access to traditional channels.

3.5. Response and Recovery

Mason et al. (2017) examined the strategic ambiguity in handling during the first 48 hours of crisis [34]. The set of studies on response and recovery from Joplin provides a range of how disaster management is multifaceted, including studies of example behavior, the role of entrepreneurs, technology, and economic recovery, elegance in comparative disaster research, and spatial and temporal vagaries of recovery, and community resilience and crisis communication. Exploring the evolution of community resilience over time and identifying successful strategies for crisis communication—particularly in the hours immediately following initial disaster response efforts—are necessary for enhancing community preparedness and response capabilities. Similarly, Abramson and Culp (2013) detailed Joplin's journey toward long-term recovery [35]. The researchers illustrated how the community began to lay the groundwork for recovery with the active involvement of various local stakeholders. Local government, healthcare representatives, business leaders, school districts, and nonprofit organizations collaborated in an unprecedented collaborative effort to rebuild and revitalize the city. Abramson and Culp's approach encompassed the physical reconstruction of the damaged infrastructure and aimed at reinforcing the social and cultural framework that forms the essence of Joplin's identity [35]. The authors detailed how the robust public engagement and strong leadership resulted in effective and expedited rebuilding efforts, paving the way for Joplin's notable resurgence. Resident's positive attitudes played a major role, as did the proactive stance of community leaders who adopted iterative planning processes to navigate and mitigate the challenges that emerged during the recovery phase. Abramson and Culp's study provided insights into the dynamics of community recovery, emphasizing the effectiveness of local governance, the importance of stakeholder involvement, and the resilience of the human spirit in the face of catastrophe.

Studies might extend to mechanisms of preparing for and fostering this kind of proactive planning and fostering entrepreneurial skills in disaster-prone areas. In information dissemination during disasters, Nguyen et al. (2015) presented TSum4act, a framework for filtering and summarizing tweets to glean actionable intelligence to alleviate information overload posed by millions of disaster-related, multi-lingual/unstructured tweets [36]. Further, Tsum4act manages the overwhelming volume and complexity of tweets generated during disasters. The primary goal is to filter through the noise and diversity of the Twitter stream to identify actionable tweets that can aid in disaster response efforts. An innovative aspect of the TSum4act framework is its use of event extraction, which enhances the semantic richness of the tweets, making the summaries more informative and actionable. Integration is key to improving the framework's performance. Nguyen et al. demonstrated TSum4act's effectiveness using a dataset of tweets from the Joplin tornado [36]. Nguyen et al. achieved higher completeness in capturing actionable information than the retweet baseline used for comparison. The framework's success illustrates its potential to serve as an important tool in disaster management efforts; it provides stakeholders with timely, relevant, and actionable information extracted from social media chatter during emergencies, which helps speed up and more effectively direct post-disaster response. However, Nguyen et al. (2015) posed a significant challenge in revealing the chasm between digital tools and traditional emergency management systems [36]. Future research could assess the possible synergies and associated challenges in integrating social media with traditional emergency management or how digital tools can complement legacy disaster response mechanisms by addressing misinformation and information overload.

According to Arendt (2023), recovery efforts commenced with notable immediacy, involving leaders and citizens across various sectors in the wake of the Joplin tornado [37]. The collective endeavor led to the community's noteworthy resurgence. A sense of resilience, marked by citizen advocacy and broad-based stakeholder engagement, was fundamental to the success of Joplin's recovery. Integral to the process was the creation and adherence to a unified vision for the future of Joplin, coupled with strategic gathering and application of information on available federal and state support initiatives. A widespread can-do attitude persisted, aimed at preserving Joplin's unique social and cultural capital, essential to its post-disaster regeneration. Throughout recovery, community leaders demonstrated adaptive planning capabilities, effectively navigating and resolving unforeseen challenges and reconsidering traditional decision-making frameworks to more holistically address the community's need to balance mourning losses with recognition of progressive strides towards recovery.

Smith and Sutter (2013) investigated how the private and public sectors contributed to the recovery efforts [38]. A key theme was Joplin's rapid recovery, attributed to a less centralized approach by government officials,

allowing the voluntary sector, including businesses, charities, and local community groups, to lead the recovery efforts. The decentralized strategy differed significantly from the more centralized, planned approach in other disaster recoveries, notably in New Orleans post-Katrina. Joplin's recovery showcased the strengths of a polycentric response system, wherein various stakeholders, including local and federal government, private businesses, nonprofit organizations, and community groups, effectively coordinated their efforts. Coordination was in efficiently deploying resources and managing the recovery process. Businesses played a major role by quickly providing relief and maintaining employment, while local authorities facilitated rebuilding by relaxing regulations and focusing on restoring public services. The response highlighted the power of community resilience and the effectiveness of decentralized decision-making in disaster recovery.

Paul and Stimers (2015) examined how Joplin residents adopted recommended safety measures in rebuilding or repairing their homes [17]. The researchers focused on the city-initiated safety features to reinforce the community's resilience to future tornadoes. The authors surveyed residents within the tornado's path, and 'the crucial determinants for adopting these measures included the damage incurred, the degree of perceived tornado risk, and whether the property was repaired or entirely rebuilt. Paul and Stimers concluded that homeowner decisions to integrate recommended safety measures were significantly influenced by those factors, indicating a selective engagement with the proposed safety improvements [17]. Understanding the behavioral responses to institutional recommendations for disaster mitigation provides insights for policymakers and emergency management officials aiming to enhance community safety and preparedness. Paul and Stimers stressed the potential for educational outreach to shape post-disaster recovery and the role of informed decision-making in constructing and rehabilitating disaster-resistant communities [17].

Coles et al. (2016) examined how partnerships among different agencies contribute to the efficacy of disaster relief operations through comparative dynamics of agency collaboration in response to the 2011 tornado in Joplin, Missouri, and the impact of Hurricane Sandy along the Jersey Coast in 2012 [39]. The researcher's central focus was the genesis, sustenance, and dissolution of agency networks amidst crises, engaging with 80 agencies and scrutinizing over 500 partnerships to assess their structure and stability. One of the pivotal findings was that only about a third of the partnerships used during these crises were formed before the disasters, indicating significant improvisation in response efforts. Coles et al. highlighted the longevity of partnerships between non-governmental organizations, suggesting a pre-existing framework for collaboration independent of immediate disaster response needs [39]. The strength and durability of these NGO partnerships emerge as key factors in the stability and effectiveness of the overall disaster response. The authors argued that understanding the pre-existing interagency relationships and the propensity to form new alliances during crises is to optimize the collaborative process for future disaster response. Coles et al. also emphasized the importance of pre-disaster strategic planning, noting that the durability of response efforts depends on the robustness of pre-established partnership frameworks [39].

Grube and Storr (2018) explored entrepreneurs' significant yet often underappreciated role in post-disaster community recovery [40]. The authors proposed that post-disaster entrepreneurs catalyze recovery by (a) providing necessary resources to disaster victims at times when they are most needed, (b) using their embedded social capital to navigate the uncertainties that are intrinsic to post-disaster contexts, (c) being driven by a deep attachment to their place of business, which motivates their involvement in community recovery efforts; and (d) pursuing both commercial interests and social objectives, reflecting a dual commitment to economic and community well-being. Grube and Storr highlighted the embeddedness of entrepreneurship in the social fabric of a community, which enables entrepreneurs to engage in recovery in uniquely effective ways. The authors offered empirical evidence from fieldwork conducted in New Orleans following Hurricane Katrina and after tornadoes in Tuscaloosa and Joplin, providing case studies that illustrated how entrepreneurs have been at the forefront of supplying resources, leveraging social networks, and exhibiting a high level of commitment to their localities. The authors contended that the success of these entrepreneurs in aiding recovery stems from their intrinsic connection to their communities, which informs their actions and sustains their efforts. Drawing on their extensive social networks and knowledge of local needs, these entrepreneurs helped to mend their communities' economic and social fabric. The researchers emphasized the need for policies that support entrepreneurial activity in post-disaster scenarios, as these individuals and enterprises are often best positioned to initiate and drive effective recovery efforts.

Richmond (2021) examined population losses and recovery policy on the post-2011 Joplin tornado [41]. Conducted through interviews with local government officials, policymakers, and business officials directly involved

in the disaster response and recovery efforts, Richmond focused on what policies and actions were most effective in aiding the recovery process and found that successful recovery measures concentrated on rapid rehousing, access to personal financial resources for survivors, and the swift execution of recovery processes. Richmond did not propose specific policy measures due to their un-generalizable nature; however, he laid a foundation for future research into effective disaster recovery policy. The Joplin tornado highlighted the importance of prioritizing housing and financial stability for survivors and streamlining recovery to minimize delays and promote economic resurgence after such catastrophic events.

Richmond and Knight (2021) examined the economic recovery following the Joplin tornado [42]. The researchers used in-depth interviews to explore how interdisciplinary teams contributed to recovery, particularly in disaster emergency management and social work. They focused on economic recovery, emphasizing the need for collaboration across various sectors and disciplines. The researchers identified key themes, including the importance of memorandums of understanding (MOUs), public-private partnerships, and public and private funding sources in disaster recovery. Relationships and network-building were crucial in facilitating effective recovery processes. Richmond and Knight suggested that policies aimed at disaster recovery should be adaptable and focused on preventing population loss, ensuring continuity in business operations, and securing housing solutions [42].

Attary et al. (2020) explored the economic consequences that delays in financial relief can have following natural disasters [31]. Using the Joplin tornado as a case study, the authors construct an analysis by integrating a civil engineering model that replicated the tornado's damage with an economic model of the local economy. The approach allowed them to trace the ripple effects of recovery delays on Joplin's economic landscape. Attary et al. offered a detailed discussion on the increasing frequency and escalating economic costs of natural disasters in the United States, particularly highlighting the problematic delays in distributing federal recovery funds [31]. Delays are not trivial; rather, they significantly exacerbate the economic downturns experienced post-disaster by amplifying unemployment and reducing output. The authors employed a dynamic computable general equilibrium (CGE) model tailored to Joplin's economy, incorporating detailed building damage assessments and economic activity data to simulate various recovery scenarios. The sophisticated modeling revealed stark differences in economic outcomes based on the timing of financial aid. Attary et al.'s simulations demonstrated that delays in financial relief deepen initial economic losses and lead to prolonged economic recovery periods, which underlines the importance of immediate financial interventions in mitigating short-term economic impacts and fostering a quicker recovery [31]. They argued for policy reforms aimed at expediting the disbursement of financial relief, suggesting that such reforms would significantly bolster economic outcomes for communities affected by disasters and enhance overall CR against future catastrophic events.

Pilkington et al. (2021) examined the extensive recovery process following the Joplin tornado, offering a unique perspective using spatial video data, capturing the gradual transformation of Joplin's landscape over five years [43]. The methods involved periodic revisits of the affected neighborhoods, documenting the rebuilding status of structures. Pilkington et al.'s approach enabled them to map out the repair times and understand the underlying patterns influencing the recovery pace. A significant finding of the study was the varying repair times for buildings, largely dependent on their age and location within the community. The researchers revealed that buildings constructed pre-1970 and those in less populated areas experienced longer repair durations. Contrary to common assumptions, Pilkington et al. pointed out that the year of construction of a building played a more significant role in determining recovery time than income levels. The scope of the tornado's impact was widespread, affecting approximately 8,000 structures and resulting in substantial economic losses. The immediate aftermath saw a rush to repair buildings with minimal to severe damage, most of which were restored within the first year [44]. However, destroyed buildings presented a varied timeline, stretching from 6 months to over 2 years for a full recovery. An essential aspect of the study focused on the influence of socioeconomic factors on recovery times. Findings underscore the importance of access to transportation and the nature of housing tenure—whether individuals owned, rented, or had other arrangements—as key determinants in the speed of rebuilding efforts.

Stimers and Paul (2022) studied building permits as a recovery indicator, adding to research on the problem of how recovery processes vary across space and time, detailing the recovery trajectory following the Joplin tornado [44]. Using building permit data as a lens, the researchers mapped the issuance of various types of permits (residential permits, commercial permits, roof repair permits, and demolition permits) against the backdrop of the tornado's destruction path as categorized by the Federal Emergency Management Agency (FEMA). Stimers and

Paul contextualized the scale of the disaster and set the stage for a deeper investigation into the recovery processes that unfolded in its aftermath [44]. The authors argued that while building permit data has been sparingly used in academic literature, it holds significant potential for informing recovery strategies and resource allocation in disaster-stricken areas. Methodologically, Stimers and Paul collected permit data from the City of Joplin immediately after the tornado in May 2011 to the end of 2020, then mapped the categories across the different damage zones designated by FEMA [44]. The approach allowed for a visual and analytical review of how recovery effort distribution throughout the city. Their findings revealed a concentration of demolition permits in areas that suffered catastrophic damage, indicative of intensive cleanup operations in these zones. Conversely, roof repair permits were predominantly issued in areas that experienced lesser damage, suggesting that initial recovery efforts focused on quickly restoring habitability to less affected structures. Over time, the issuance of residential and commercial building permits provided insights into the longer-term rebuilding phase, highlighting areas where new construction was concentrated and thus signaling a return to normalcy. However, the authors acknowledged their study's limitations, particularly its focus on a singular, unique tornado event, which may not directly translate to other disaster scenarios.

Stimers et al. (2022) presented a detailed analysis of post-disaster recovery using advanced statistical methods on a similar research track [45]. The authors employed the SaTScan software's space-time permutation model to analyze building permit data, which served as a proxy for rebuilding efforts in Joplin following the tornado. The researcher's primary objective was to identify significant space-time clusters in issuing building permits, providing insights into the patterns and pace of recovery. Applying the space-time permutation model facilitated the researchers to detect areas where rebuilding activities were concentrated and assess the temporal dynamics of these efforts. Results revealed how different areas within Joplin responded to the disaster over time and how various factors, including the severity of the damage, availability of resources, and socioeconomic conditions, influenced the spatial and temporal patterns of building permit issuance. Identifying clusters helped highlight areas that may have experienced delays or accelerations in rebuilding, offering valuable information for policymakers and planners aiming to improve disaster recovery strategies. The researchers then graphed the results against the backdrop of the Kates (1977) recovery model—the first application of such a comparison using tornado recovery data [46]. Stimers et al.'s research contributes to the broader literature on disaster recovery by demonstrating the utility of advanced spatial-temporal analysis tools in assessing post-disaster rebuilding efforts [45].

Dinger et al. (2012) explored the relationship between community identity and entrepreneurial decision-making after natural disasters, exploring how entrepreneurs' perception of themselves as part of a community influences their choices, particularly the decision to rebuild their business after a disaster [47]. They surveyed 112 business owners from Joplin, examining the factors influencing their decisions to rebuild their businesses. The analysis revealed two dimensions of social identity impacting these decisions, including (a) group attractiveness and (b) interdependency beliefs. Group attractiveness refers to the entrepreneur's positive perception of and satisfaction with community participation. Interdependency beliefs relate to the entrepreneur's sense of shared destiny with the community. Dinger et al.'s findings substantiated the hypotheses, showing that entrepreneurs who perceived a higher level of group attractiveness and interdependency were more likely to decide to rebuild [47]. Notably, traditional financial and economic factors, such as insurance payouts, did not significantly impact those decisions, indicating a paradigm shift in understanding entrepreneurial behavior in disaster contexts and highlighting the influence of social-psychological factors over economic ones. The researcher's contributions extend beyond disaster recovery, offering insights into the broader field of entrepreneurship and demonstrating that entrepreneurial decisions, often considered purely economic, are deeply influenced by social and psychological factors. Results revealed the importance of nurturing a strong community identity as a resilience strategy in disaster scenarios and fostering a supportive environment for entrepreneurial endeavors.

Pilkington and Mahmoud (2021) explored the integration of socio-technical factors in modeling the recovery times of buildings following extreme wind events using artificial neural networks (ANNs) [48]. The study was set against the backdrop of the 2011 Joplin tornado, offering a practical context to validate the theoretical models proposed. The researchers applied two distinct ANNs designed to predict building recovery times. The first model primarily incorporated social variables, while the second included structural and social variables. The researchers assessed the models through graph theory, employing concepts such as centrality and the shortest path to evaluate the importance and interaction of various input variables in the recovery process. Key findings highlighted

that while social variables significantly influenced damage models, their impact on recovery models was less pronounced, suggesting complexity between social and structural variables during recovery, which is more complex than during damage assessment. Wang and van de Lindt (2021) researched the dynamics of community resilience and disaster recovery, focusing on the recovery process for residential buildings affected by disasters, using the Joplin tornado as a case study [6]. The authors employ a two-stage recovery modeling approach incorporating a sophisticated multi-layer Monte Carlo simulation technique to examine the functional downtime due to repair delays and the functional downtime due to the repair process. The delays are modeled on factors such as post-disaster inspection times, insurance claims, and the acquisition of building permits, underlining the significant impact these factors have on the overall recovery time. Wang and van de Lindt (2021) also investigated how household income levels affected the ability to finance repairs, reflecting on the socioeconomic disparities in disaster recovery [6]. Innovatively, the researchers integrated the REDi framework—originally developed for earthquake recovery—to adapt to tornado-induced damages. The adaptation allows for a detailed analysis of how pre- and post-disaster policies influence the speed and efficiency of recovery efforts. The policy implications are discussed in depth, offering insights into how strategic policy adjustments can significantly improve community resilience and reduce recovery time.

Like Wang and van de Lindt (2021), Aghababaei et al. (2020) focused on calibrating building repair fragility models using data from the Joplin tornado, focusing on the post-disaster recovery process of buildings impacted by the Joplin tornado [6, 49]. The researchers refined the predictive models for building repair and recovery by aligning them more closely with empirical data collected from the field, thus improving the realism and utility of these models in planning and response efforts. Aghababaei et al. documented an existing recovery dataset from Joplin and used it to highlight discrepancies between observed recovery trajectories and those predicted by existing analytical models [49]. A significant portion of the study involved the calibration of the models to better reflect real-world conditions, particularly by incorporating various delays encountered in the repair process, such as inspection delays, time to obtain financial resources, and delays in finding and hiring contractors. Using a detailed methodology that integrated empirical functionality fragility curves with analytical predictions, the authors presented a revised analytical framework that better matches the observed data.

3.6. Fatality Studies

Paul and Stimers (2012) investigated the high number of deaths resulting from the Joplin tornado [50]. The authors examined several contributory factors and proposed that the tornado's sheer magnitude, its trajectory through densely populated areas, the structural vulnerabilities of the impacted buildings, and issues with the warning system significantly influenced the tragic outcome. They provided contextual background on tornado-related risks and fatalities, noting that factors like timing, magnitude, and population density in the tornado's path play crucial roles in determining the severity of impact. The researchers also considered the physical characteristics of buildings in Joplin, highlighting how older, less robust structures without basements or adequate anchoring contributed to the high casualty rates. The authors explored human factors, such as the response to tornado warnings, revealing that despite a relatively high compliance rate, some fatalities occurred due to a mix of disbelief in the severity of the situation and inadequate sheltering spaces. Their study method involved detailed surveys, interviews with survivors, and analyses of spatial data and emergency management strategies.

Curtis and Fagan (2013) examined patterns of damage and mortality resulting from the Joplin tornado [51]. The researcher's innovative approach leveraged spatial video technology combined with a newly developed Tornado Injury Scale (TIS), adapted from the Enhanced Fujita Scale, to examine the effects of the tornado at a granular level. The authors provided insightful analyses of how certain types of building damages correlated with fatalities, emphasizing the vulnerability of demographic groups, notably older residents, by linking these detailed observations with mortality data. Curtis and Fagan highlighted the variability in damage patterns, noting that certain areas experienced different levels of devastation, directly affecting survival during the tornado. Findings suggested that traditional methods of post-tornado damage assessment underestimate the variations in damage that can occur within small geographic areas. The researchers addressed broader implications for tornado preparedness and response [51]. Curtis and Fagan argued for the potential of spatial video technologies in enhancing traditional GIS applications in disaster response, advocating for improved classification of tornado damage that could aid more accurate and timely responses in future disasters [51].

Paul and Stimers (2014) examined the spatial distribution and demographic characteristics of the fatalities from the Joplin tornado [52]. Using interpolated damage zones to map the fatalities, the researchers examined the correlation between the tornado's path of destruction and the resulting human toll. Through a detailed analysis of death locations, the researchers illustrated how fatalities were distributed across various damage zones defined by the extent of the destruction, providing insights into the tornado's devastating impact on different parts of the city. Central to their findings was the observation that most deaths occurred in nonresidential buildings, a departure from typical tornado fatality trends, which more commonly involve residential structures. The anomaly was explored and focused on the tornado's path severely impacting commercial areas, leading to higher-than-average casualties in business settings. The authors also highlighted the lack of basements in many of the affected structures, which likely contributed to the high fatality rate, as many victims had insufficient shelter from the storm's peak intensity. The researchers addressed the demographic vulnerabilities, noting that older adults had disproportionately high mortality rates, which underscored the need for targeted disaster preparedness and response strategies to protect these high-risk groups.

Paul and Stimers (2017) examined the influence of elevation on the distribution of fatalities caused by the Joplin tornado [53]. They employed spatial analysis to explore the correlation between elevation levels and the locations of fatalities. The researchers used GIS to map the elevation of various sites in Joplin where fatalities occurred, providing a detailed examination of how topographical features may have affected the tornado's impact. The researchers determined if certain elevations were more vulnerable to high fatality rates by overlaying fatality data with elevation maps. Findings indicated that elevation played a significant role in the distribution of fatalities—areas with lower elevations experienced higher fatality rates than those at higher elevations. Results align with several factors, including the possibility that lower-lying areas may have had older or less structurally sound buildings or that residents had fewer resources or less access to adequate shelter. The researchers noted the importance of considering topographical factors in disaster preparedness and response planning. Understanding the relationship between elevation and tornado impact can help urban planners and emergency management officials identify vulnerable areas and implement more effective mitigation strategies, including reinforcing building codes in low-lying areas, improving public awareness and preparedness measures, and ensuring adequate shelters are available and accessible.

Fatality research on the Joplin tornado has produced important findings, yet the field remains constrained by an overreliance on isolated variables rather than integrated causal frameworks. Paul and Stimers (2012) acknowledged the interaction between structural vulnerability, storm intensity, and human behavior, but their conclusions did not resolve how preparedness measures could realistically mitigate fatalities in communities with aging housing stock and limited access to shelter [50]. Although their findings confirmed the role of disbelief and shelter inadequacy, they stopped short of evaluating which behavioral interventions might increase protective action across diverse populations. Curtis and Fagan (2013) introduced spatial video and the Tornado Injury Scale to pinpoint localized mortality risks, showing that damage and death vary sharply within small geographic zones [51]. Their methodological innovation outpaced traditional damage surveys, yet the study did not fully account for how emergency planners might operationalize these tools in real-time. Similarly, Paul and Stimers (2014) disrupted typical assumptions by revealing that most fatalities occurred in nonresidential buildings [52]; this pattern shift raised important questions about risk concentration in commercial areas but went unlinked to policy recommendations on commercial building codes or business preparedness protocols. The elevation-focused analysis by Paul and Stimers (2017) introduced terrain as a new spatial lens, finding that lower elevations correlated with higher fatality rates [53]. While valuable, the explanation remained speculative, pointing to possible associations with older buildings or socioeconomic status without empirically testing those links. Across the fatality studies, researchers have identified important risk patterns—commercial vulnerability, demographic disparities, and topographic variation—but have yet to unify these into predictive models or recovery frameworks that integrate environmental, structural, and social data. A major gap remains in translating granular spatial findings into actionable zoning, sheltering policy, or public education initiatives that could materially reduce future tornado-related deaths.

3.7. Human Health

3.7.1. Disaster Preparedness and Response for Medical Practices

Avitzur (2011) emphasized the importance of disaster preparedness for neurologists and medical practices, recounting real-life experiences of neurologists during disasters such as tornadoes and floods, underscoring the necessity for emergency plans and quick thinking in such situations [54]. Neurologists like Dr. Daniel L. Dagen and Dr. Taylor C. Bear shared their experiences during the Joplin tornado, where they improvised evacuation plans and provided medical assistance amidst chaos and destruction. Dr. Bear's proactive measures showcased the importance of preparedness, such as retrieving medical equipment and patient data before communication line restoration. Avitzur suggested practical steps for disaster preparedness, including assessing vulnerability based on geographical risks, familiarizing oneself with local hospital disaster plans, and duplicating and backing up essential documents [54]. He also stressed the importance of adequate insurance coverage and emergency preparedness training for physicians. The author provided a checklist of basic supplies recommended by the American Red Cross for emergency preparedness kits, emphasizing essentials like water, non-perishable food, communication tools, first aid supplies, and tools for utility management.

According to Barbe (2012), following the Joplin tornado, Mercy Health demonstrated extraordinary resilience and commitment to the community by immediately announcing plans to rebuild the hospital and maintain wages for its staff [55]. Within 1 week, a mobile medical unit was operational, and within 2 months, Mercy primary care physicians were back in their offices. By October, a temporary hospital was functioning, succeeded by a modular hospital constructed within 8 months, reflecting robust recovery efforts and fostering community morale. Rapid redevelopment ensured continuity of care, with comprehensive medical facilities reinstated less than 1 year after the disaster, highlighting Mercy Health's pivotal role in the community's recovery.

Charney et al. (2014) researched the resilience and response of healthcare workers following the Joplin event [56]. The tornado necessitated a complete evacuation of one hospital and caused a significant patient surge to another. They assessed various aspects of the healthcare workers' readiness and response, including their willingness to work post-disaster, personal disaster preparedness, and the impact of childcare responsibilities on their ability to report to work. Using a survey distributed to hospital personnel two years after the tornado, the researchers gathered data on the workers' actions during the disaster and their attitudes toward working during future disasters. Results revealed that a high percentage of healthcare workers (87.8%) reported to work in the week following the tornado, demonstrating a strong professional commitment amidst personal challenges. Healthcare workers' responses were significant, considering many suffered losses and disruptions. A notable finding from the study was the increased willingness among healthcare workers to report to work during future earthquakes or tornadoes, compared to their attitudes prior to the Joplin tornado. The shift suggests that experiencing the tornado may have heightened their sense of duty or preparedness for similar events in the future. However, Charney et al. also stated that personal disaster preparedness significantly predicted this willingness, emphasizing the importance of preparedness measures [56]. Childcare emerged as a crucial factor influencing healthcare workers' ability to work during the disaster. Nearly half of the respondents had childcare responsibilities, and those with robust alternative childcare plans were more likely to report to work and felt more secure about their children's safety during their absence.

3.7.2. Stress, Mental Health, Psychological Resilience, and Coping Mechanisms

Houston and Franken (2015) analyzed the relationship between interpersonal communication and posttraumatic stress symptoms (PTS) in the aftermath of the Joplin tornado [1]. The researchers conducted a detailed survey approximately 6 months after the tornado, targeting adult residents of Joplin. Houston and Franken focused on understanding the extent to which individuals engaged in interpersonal communication about the tornado and how such communication related to their experiences of posttraumatic stress [1]. The survey content explored various aspects of communication, including discussions with family, friends, and neighbors and participation in community meetings. Findings suggest a significant correlation between higher levels of PTS symptoms and increased interpersonal communication about the tornado. Those directly affected by the storm or who knew someone who died were particularly likely to engage more in discussions about their experiences. The researchers highlighted important sociodemographic influences on communication behaviors. For instance, women and more educated individuals engaged more frequently in discussions about the tornado, suggesting that social roles and access to

resources affect how people cope with disaster experiences. Younger people were more likely to talk about the disaster with neighbors, indicating that age might influence the choice of support networks during recovery.

Houston et al. (2015) surveyed the Joplin population at two post-disaster intervals: approximately 6 months and then again 2.5 years after the event [57]. They explored several dimensions, including mental health outcomes such as PTS and depression, the extent of tornado experience, and the use of mental health services among survivors. Findings indicated a troubling trend of persistent and escalating mental health issues among the affected population. During the 6-month survey, the prevalence of probable posttraumatic stress was significantly high and continued to rise, as evidenced by the findings from the second survey. Depression rates, while still considerable, showed a slight decrease over time. The researchers also revealed the low levels of mental health service use among those with significant symptoms of PTS and depression. Despite the evident need, many survivors did not seek or receive adequate mental health support, possibly due to barriers such as stigma, limited access to services, or ongoing disruption in the local healthcare infrastructure. Houston et al. extended their analysis to the social supports and experiences of the children within the affected families, finding that younger children, particularly, exhibited high levels of distress as reported by their parents, stressing the pervasive impact of such traumatic events across all age groups.

Moulton (2015) researched the process of memory work in the tornado's aftermath [58]. The author explored how the survivors and the broader community constructed a collective memory and identity following the disaster, a process crucial to communal and individual recovery. Moulton discussed the formation of memory through public ceremonies, monuments, and individual storytelling, which not only served to commemorate the event but also aided in the emotional recovery of the community. Memory work helped integrate traumatic memories into a narrative framework, linking pre-disaster identities with post-disaster experiences, thereby facilitating a smoother psychological recovery and the redefinition of community identity. He noted survivors' use of social media and other platforms to share their narratives, which Moulton collected and analyzed. Through those narratives, Moulton observed emerging patterns and common themes that solidified into a collective memory, influencing how the community perceives and recovers from the disaster. The process was akin to certain psychotherapeutic techniques used to treat PTSD, wherein creating a narrative from traumatic memories can alleviate anxiety and integrate these experiences into one's life narrative. Moulton also touched on the physical inscription of memory in the landscape, such as through memorials and monuments that honored the past and symbolized the community's resilience and recovery [58]. Establishing these memoryscapes helped solidify the collective narrative and fostered a shared identity important for long-term recovery.

Brown (2017) studied the psychological and sociocultural dynamics of how individuals relate to nature following a significant natural disaster [59]. His study in Joplin evaluated the interrelations among connectedness to nature, demographic variables, religious and spiritual beliefs, and psychological resilience within a community affected by the 2011 tornado. Using a sample gathered from visitors to the Cunningham Park Butterfly Garden and Overlook—a nature-based intervention designed to aid community healing post-disaster—Brown assessed participants using the connectedness with nature–single-item scale, the brief resilience scale, and a measure of spirituality and religiosity. She used linear regression analysis to discern the predictive power of these variables on individuals' feelings of connectedness to nature. Results identified education and spiritual or religious beliefs as significant predictors of nature connectedness but not psychological resilience. Connections to nature were notably more pronounced among those who did not directly experience the tornado, suggesting that personal exposure to the disaster could alter one's relationship with the natural environment. Individuals attribute meaning to the disaster, viewing it through a religious lens as a divine act or a natural occurrence. Brown's discussion extended into the implications of these findings for disaster recovery and community resilience.

Langan et al. (2017) explored the resilience levels among survivors of the Joplin tornado [4]. Conducted 3 years post-disaster, the researchers sought to understand the relationship between age and resilience, employing a mixed-methods approach that included surveys and focus groups among different age segments of the community. Results revealed that most of the 182 survey respondents exhibited normal to high levels of resilience 3 years after the tornado. The researchers found no significant differences in resilience levels across different age groups, challenging some common assumptions about age-related variability in coping mechanisms [4]. Focus group discussions enriched the findings, providing qualitative insights into the personal narratives of resilience and recovery. Narratives depicted a spectrum of psychological adaptation, from enhanced resilience and a return to a baseline

state of normalcy to struggling with reduced coping capabilities and ongoing psychological distress.

First et al. (2018) investigated the phenomenon of posttraumatic growth (PTG) in the context of the Joplin disaster [60]. The researchers examined the relationship between disaster experience, posttraumatic stress symptoms, and communication among survivors with their social networks, as well as their subsequent growth following the tornado. Drawing from a sample of 438 adults, they used an online survey to measure the levels of PTG at a considerable distance—2.5 years—from the disaster event. The research leverages the Posttraumatic Growth Inventory (PTGI) to quantify growth, assessing new possibilities, personal strength, spiritual change, and appreciation of life. Results underscored that greater exposure to the tornado and more intense posttraumatic stress symptoms positively correlated with higher PTG. First et al. also revealed that active communication about the tornado with family, friends, and neighbors was associated with greater perceived growth, suggesting that social interactions were important in the recovery and growth process by possibly providing emotional support and aiding in the cognitive processing of the event [60]. First et al. promoted the encouragement of open communication among disaster survivors and suggested that interventions should leverage existing social networks to facilitate recovery.

Bigelow (2019) reflected on his deployment experience, starting 1 week after the 11 May 2011 Joplin tornado hit [61]. Despite his prior disaster response experience, the scale of Joplin's devastation profoundly affected him. He provided psychological first aid, encouraged survivors to express their emotions, and offered practical support and self-care advice. The researcher described the importance of community outreach and sheltering, highlighting his work distributing supplies and connecting with survivors. His interactions often revealed the resilience and generosity of the community, such as neighbors helping each other despite their losses. Bigelow also noted the role of informal support networks, like the Mennonite families providing meals and law enforcement officers dealing with the grim task of recovering bodies [61]. Throughout the narrative, Bigelow emphasized the need for disaster mental health (DMH) workers to be proactive, empathetic, and flexible. His strategy of boldly wading in allowed him to connect with survivors and provide crucial emotional support. He also highlighted the necessity for DMH workers to manage their mental health, acknowledging the impact of secondary trauma from listening to survivors' stories. Bigelow concluded with lessons learned, stressing that genuine empathy and self-care are essential for DMH workers.

Huff (2020) reflected on his experiences as a school superintendent in Joplin during and after the tornado, describing the emotional and psychological challenges faced during the disaster recovery process and the lessons learned about self-care and leadership in times of crisis [62]. Huff described the day of the tornado, which coincided with the graduation ceremony of Joplin High School, turning from a celebratory occasion into a tragic event. The aftermath left the community and its leaders in shock, tasked with rebuilding the physical structures and the community spirit. He discussed his initial struggle with the overwhelming responsibilities and the gradual realization of the importance of self-care. Huff recounted neglecting his physical and mental health, which eventually led to severe consequences, including depression and bulimia [62]. He advocated for the proactive maintenance of physical health, mental well-being, and spiritual balance, particularly highlighting the necessity of establishing and adhering to these practices even before crises occur. Huff reflected on the importance of vision and relationships in navigating through disasters, stressing that clear, compelling leadership was essential to mobilize and sustain community support and action [62].

First et al. (2024) analyzed qualitative responses from 359 residents collected 2.5 years after the Joplin disaster to understand the persistent unmet needs commonly encountered during long-term disaster recovery [63]. Findings revealed psychological distress that pervaded the community, a condition residents refer to as tornado brain; this term captures the lasting impact of the tornado, manifesting as anxiety, depression, and PTSD among the survivors. First et al. noted a gap in the availability and accessibility of mental health services equipped to handle the magnitude and duration of such trauma. The persistence of mental health issues shows the need for extended support frameworks that can provide ongoing care and facilitate psychological resilience. The tornado's destruction extended significantly to the housing sector, leaving a lasting deficit in affordable and safe housing. First et al. emphasized the need for quantity and quality in housing reconstruction efforts. Safe shelters and affordable housing options were crucial for stabilizing the affected populations' socioeconomic conditions and reinforcing community resilience against future disasters. Effective rebuilding efforts must transcend the physical reconstruction of buildings and infrastructure, including strengthening community bonds, restoring social support systems, and rejuvenating community spirit and identity. Economically, the tornado inflicted severe long-term financial hardships

on many families. Increased living costs, coupled with lost income due to the disaster, have exacerbated the economic vulnerability of the residents. The researchers called for more robust financial support systems that address immediate disaster relief and long-term economic recovery, helping individuals and families regain financial stability. First et al. called for reevaluating current disaster recovery models, suggesting a more integrated approach considering the interdependencies of mental health, housing, community cohesion, and economic stability. Such an inclusive framework is essential to address the myriad challenges of disaster recovery, ensuring communities like Joplin recover and thrive in the aftermath of such significant traumatic events.

3.7.3. Mental Health Impacts on Especially Vulnerable Populations

Kanter and Abramson (2014) examined schools' role in recovering and supporting children following the Joplin tornado [64]. The researchers presented a case study highlighting the proactive and strategic interventions employed by school administrators to address the immediate and ongoing needs of students impacted by the disaster. Kanter and Abramson described how the Joplin school district leadership rapidly decided to resume educational services as swiftly as possible. District leaders expanded summer school programs and adapted curriculums to re-focus on emotional well-being and safety rather than solely on academic progress, recognizing the tornado's psychological impact on students. Kanter and Abramson also explored the logistical challenges and solutions in reopening schools for the new academic year less than 3 months after the tornado. Reopening included setting up temporary facilities and ensuring displaced students could continue attending their original schools, regardless of their temporary housing situations [64]. The authors detailed how the district facilitated transportation for these students and undertook extensive efforts to locate and contact every student and staff member to help and gather information necessary for effective planning and support. A significant aspect of the interventions included training school staff on mental health support techniques and deploying certified counselors to conduct school-based, small-group counseling sessions. District leaders' efforts provided direct support to students displaying signs of anxiety, depression, or other emotional distress. Kanter and Abramson's case study illustrated how well-planned school-based interventions can significantly contribute to children's mental and behavioral health after disasters, facilitating a quicker and more effective community recovery [64].

Adams et al. (2015) studied the psychological aftermath faced by adolescents following the devastating tornadoes of 2011 to estimate the prevalence of comorbid posttraumatic stress disorder (PTSD), major depressive episode (MDE), and substance use disorder (SUD) among a population-based sample of adolescents affected by major disasters [65]. Using structured telephone interviews with both adolescents and their parents, the researchers gathered data on the presence and comorbidity of PTSD, MDE, and SUD. Findings revealed notable rates of PTSD, MDE, and SUD, specifically concerning the comorbidity patterns among the affected youth. They found that 3.7% of the adolescents surveyed experienced comorbid PTSD and MDE, 1.1% had PTSD and SUD, 1.0% had MDE and SUD, and 0.7% suffered from all three conditions concurrently since the Joplin tornado event. The researchers highlighted several risk factors associated with these psychiatric comorbidities. Female adolescents, for instance, were significantly more likely than their male counterparts to experience comorbid PTSD and MDE, as well as MDE and SUD. Adams et al. pointed out that prior trauma exposure, particularly non-disaster-related traumatic events, significantly increased the risk for these comorbid conditions [65].

Hambrick et al. (2018) focused on how children process traumatic memories and how processing relates to their mental health following a catastrophic Joplin tornado [66]. The researchers analyzed children's verbal recollections of the event, examining the nature and implications of their narrative coherence, emotional expression, and the presence of resolutions within their stories. Hambrick et al. uncovered significant associations between how children articulated their tornado experiences and their subsequent mental health outcomes. The researchers assessed children's narratives for coherence, which involved logical sequencing and thematic consistency, as well as positive and negative emotional terms and narrative resolutions, which indicated an ending or closure to the recounted events. Results showed that greater narrative coherence and the use of positive emotional terms were paradoxically associated with higher levels of mental health symptoms, suggesting that a more vivid recollection of trauma could be indicative of deeper emotional disturbance. Conversely, the presence of resolutions in children's narratives about their traumatic experiences linked to fewer reported symptoms, implying that narratives that conveyed a sense of closure may have helped children better cope with their experiences. Findings underscored the complex role that narrative processing plays in children's psychological adjustment post-trauma; the ability to con-

struct a coherent and resolved narrative may reflect not only a child's current mental health status but also their coping mechanisms, influencing long-term outcomes.

Christopher et al. (2019) examined the effects of prenatal exposure to significant tornadoes on birth outcomes [67]. Using data from the National Center for Health Statistics (NCHS), the researchers investigated whether exposure to the 2011 tornado outbreaks in Alabama and Missouri affected the incidence of adverse birth outcomes such as low birth weight, preterm births, and cesarean sections. Christopher et al. employed a retrospective, cross-sectional cohort design and analyzed data from two tornado-affected regions [67]. The analysis included comparing birth outcomes of exposed and unexposed mothers within these regions, using chi-square and logistic regression analyses to estimate the associations. Key findings revealed that prenatal exposure to tornadoes in Alabama correlated with a reduced likelihood of preterm births. In Joplin, exposed mothers were more likely to have a cesarean section. The researchers found no significant association between tornado exposure and adverse birth weight or infant mortality rates across both regions. Findings also suggested that while some birth outcomes, like preterm birth rates, may improve in some settings post-disaster, others, such as the rate of cesarean sections, may increase, indicating varying impacts of stress and trauma on maternal health.

3.7.4. Mucormycosis and Apophysomyces

The research surrounding the mucormycosis outbreak in Joplin examines the fungal pathogen Apophysomyces from various perspectives, including genomic analysis, clinical implications, epidemiology, and therapeutic strategies. Etienne et al. (2012) investigated the Apophysomyces outbreak following a tornado in Joplin [68]. The researchers used whole genome sequencing (WGS) to conduct a high-resolution phylogenetic analysis of Apophysomyces trapeziformis isolates collected from victims of the Joplin tornado. Apophysomyces causes severe and often fatal infections when soil or plant material containing its spores to embed under the skin through traumatic injuries. Etienne et al. detailedly examined 17 outbreak-related isolates and five control isolates of Apophysomyces, which included both A. trapeziformis and A. variabilis species [68]. The whole genome SNP phylogenetic analysis revealed significant findings, identifying three clusters of genotypically related A. trapeziformis isolates among the Joplin cases, indicating multiple, genetically distinct strains were involved in the outbreak. Results suggested that the outbreak was not caused by a single strain or point source, complicating the epidemiological understanding of such infections. Etienne et al. demonstrated that the Joplin isolates were more closely related to each other than to control isolates from other geographic areas, supporting the hypothesis of a localized source or sources within the tornado-affected area [68].

Fanfair et al. (2012) explored a severe outbreak of necrotizing cutaneous mucormycosis following the tornado [69]. They detailed the investigation into a rare and deadly fungal infection among individuals who sustained injuries during the tornado. The researchers defined mucormycosis as caused by the aggressive mold known as mucormycosis, which typically thrives in soil and decaying organic matter but can become a deadly pathogen when introduced into human tissue through traumatic injuries. The researchers identified 13 individuals with confirmed cases of the infection, characterized by aggressive and necrotizing soft tissue damage, of which five resulted in fatalities [69]. Through a case-control study involving medical record reviews and patient interviews, significant associations emerged between the occurrence of mucormycosis and specific types of traumas—notably, penetrating wounds and the presence of multiple injuries. Each additional wound increased the risk of infection, emphasizing the catastrophic nature of the injuries sustained and the severe conditions under which these fungi thrive. The outbreak highlights the need for rapid and accurate diagnosis and treatment in the aftermath of natural disasters, where unusual pathogens may exploit the chaotic post-event environment. Fanfair et al. emphasized that early recognition of mucormycosis symptoms and prompt medical intervention are crucial, as delayed treatment can lead to higher mortality rates. Findings underline the broader implications for disaster response protocols, including the importance of healthcare preparedness and the ability to manage rare but severe infections following major natural events. Research by Weinhold (2013) and in a short Notes report to the CDC, Benedict et al. (2011) [70, 71], the researchers also reviewed the outbreak. The Joplin tornado event marks the first known cluster of tornado-related cutaneous mucormycosis, highlighting the need for healthcare providers to consider environmental fungi in post-disaster injury care. Early diagnosis and treatment are crucial for improving outcomes in such infections. Epidemiological studies are ongoing to understand the risk factors better. The high mortality rate associated with these infections underscores the importance of rapid medical response and the need for healthcare

providers to consider environmental fungi as potential pathogens in disaster-related injuries.

4. Discussion: Critiques and Critical Analysis

On May 22, 2011, the city of Joplin, Missouri, faced one of the deadliest tornadoes in U.S. history. The tornado caused extensive physical destruction, significant economic losses, and impacts on human health. The present narrative literature review synthesizes the lessons from this catastrophic event, offering insights into vulnerability and resilience, building codes, preparedness, risk communication, economic assessment, and response and recovery strategies (**Table 1**) [2, 10, 13, 14, 16, 17, 19–24, 31, 32, 34, 40, 43, 45, 47, 51, 56, 60, 62, 63]. Below the authors discuss each major section through critical analysis of the content area.

Table 1. Disaster Recovery Phases and Mapped to Select Studies.

Disaster Recovery Phase	Key Lessons Learned	Example Studies
Mitigation	Improved building codes and structural resilience could have reduced damage severity	Prevatt et al. (2012) [13]
	Observed damage data helped validate EF-scale ratings and identify vulnerabilities in building practices	Prevatt et al. (2012) [14]
	Building attributes, including construction type and foundation, were statistically linked to vulnerability	Egnew et al. (2018) [2]
	School buildings were not uniformly protected; critical facilities failed under wind loads	Coulbourne and Miller (2012) [10]
	Damage assessment at the parcel level allowed for post-disaster analysis of building exposure	Stimers and Paul (2022) [44]
	Space-time patterns of building permits showed systematic redevelopment over time	Stimers et al. (2022) [45]
Preparedness	Residents often misunderstood siren warnings and lacked clear guidance on when to shelter	Kuligowski et al. (2014) [20]
	Shortcomings in alert systems led to delays in protective action decision-making	Kuligowski (2020) [22]
	Many residents relied on multiple sources for warning information, especially when unsure	Luo et al. (2015) [21]
	Pre-existing family emergency plans improved sheltering outcomes	Cong et al. (2014) [23]
	Preparedness levels were uneven across households, affecting shelter choice and warning responses	Cong et al. (2017) [24]
	Sheltering decisions were impacted by how warnings were framed, not just whether they were received	Casteel (2018) [19]
Response	Decision-making to shelter-in-place or evacuate varied with risk perception and warning interpretation	Paul et al. (2014) [16]
	Residents acted based on previous tornado experiences and confidence in warnings	Paul and Stimers (2015) [17]
	Crisis-induced uncertainty challenged first responders during triage and coordination	Mason et al. (2017) [34]
	Tornado mortality correlated with structural failure and limited access to adequate shelter	Curtis and Fagan (2013) [51]
Recovery	Building permit data illustrated the trajectory and geography of long-term rebuilding	Stimers and Paul (2022) [44]
	Cluster analysis revealed neighborhood patterns in housing recovery	Stimers et al. (2022) [45]
	Entrepreneurial action supported community-level renewal and embedded recovery	Grube and Storr (2018) [40]
	Local identity and civic engagement played a central role in organizing recovery activities	Dinger et al. (2012) [47]
	Delays in financial relief had measurable economic effects on household recovery	Attary et al. (2020) [31]
	Infrastructure interdependencies between buildings and power systems shaped recovery	Attary et al. (2019) [32]
	Video documentation provided preliminary evidence of staggered, uneven recovery across sectors	Pilkington et al. (2021) [43]
	Hospital staff faced persistent stress and operational challenges during recovery	Charney et al. (2014) [56]
	Long-term psychological effects included posttraumatic growth and ongoing mental health needs	First et al. (2018); First et al. (2024) [60, 63]
	School leaders reported enduring emotional strain and professional role conflicts post-disaster	Huff (2020) [62]

4.1. Vulnerability and Resilience

The existing body of research on vulnerability and resilience after the 2011 Joplin tornado reveals strong methodological advancements in structural and policy modeling yet lacks cohesion when integrating psychosocial data into these frameworks. Langan et al. (2017) and Houston et al. (2017) explored self-perceived resilience

and community outlooks, offering valuable insight into subjective recovery [3, 4]. However, these efforts remain disconnected from the structural modeling approaches advanced by Wang et al. (2022) and Wang and van de Lindt (2021) [5, 6]. While Langan et al. reported no significant age-related differences in resilience, Houston et al. identified age and media engagement as predictors of perceived community strength, suggesting inconsistency in how demographic variables influence resilience perceptions—neither effort accounted for how subjective resilience correlates with objective recovery timelines or outcomes. In contrast, Wang et al. used simulation models to quantify the benefits of retrofitting and policy implementation, generating clear metrics on recovery time and infrastructure performance. However, these models exclude individual and household-level psychological adaptation, leaving a gap in understanding how mental and emotional resilience might intersect with structural recovery. Egnew et al. (2018) filled part of this void by tying physical damage to building characteristics yet did not link this vulnerability data to broader community-level recovery perceptions [2]. Abdelhady et al. (2023) emphasized the need for scalable models applicable across multiple hazards, but the push toward generalization risks further sidelining localized psychological and communicative factors [8]. The literature remains divided between psychosocial insight and technical modeling, with little attempt to reconcile the two. Future work would benefit from hybrid frameworks that simulate physical recovery and account for psychological readiness, community cohesion, and public trust, which likely mediate the success of technical interventions.

4.2. Building Codes

The body of research on building codes following the 2011 tornadoes consistently identified structural weaknesses in engineered and non-engineered buildings but varied in depth regarding these failures' enforcement and policy implications. Smith et al. (2012) and Coulbourne and Miller (2012) emphasized that institutional buildings such as hospitals, emergency centers, and schools were not uniformly protected, with failures seen even in recently constructed facilities [9, 10]. While these findings suggested inadequacies in current codes, neither study addressed the structural-to-policy gap—specifically, how engineering recommendations are often diluted or ignored during code adoption and enforcement at the local level. Dao et al. (2014) introduced orientation and site-specific factors as underappreciated variables but stopped short of connecting those observations to scalable building code modifications [11]. In contrast, Prevatt, Coulbourne, et al. (2012) delivered a detailed technical analysis showing that roofing system failures often initiated cascading collapse, reinforcing the need for minimum standards prioritizing load path continuity [12]. Prevatt, van de Lindt, et al. (2012) and Roueche and Prevatt (2013) expanded the lens to include economic losses and social disruption, arguing for a multidisciplinary framework—but without specifying how such a framework could be institutionalized or funded across varying municipal contexts [13, 15]. Prevatt, Roueche, et al. (2012) identified poor connection detailing as a core vulnerability in residential construction, suggesting enhanced use of structural panels and vertical load continuity [14]. However, no study offered a clear roadmap for integrating these retrofits into code mandates without pricing out vulnerable homeowners.

4.3. Preparedness, Risk, and Warnings

A clear gap emerges in synthesizing behavioral data with communication infrastructure. For example, Luo et al. revealed that multiple sources help in some regions [21]. However, not others, yet no study has mapped how source redundancy intersects with trust in institutions, local media landscapes, or prior misinformation exposure. Similarly, while Kuligowski and Kimball outlined ideal message structures, less attention was paid to testing these in diverse cultural or linguistic contexts [18]. The literature lacks a unified framework connecting individual-level predictors (e.g., age, gender, prior experience) with system-level interventions (e.g., PADM-based alerts, standardized siren protocols) and community-level variables (e.g., local trust, institutional access). Addressing this gap would require interdisciplinary studies that combine behavioral science, communications theory, and public policy design to produce adaptable warning systems tailored to hazards and the lived experience of those at risk. The literature on building code performance during the 2011 tornado outbreaks presents well-documented technical failures but lacks a unified strategy for converting engineering findings into enforceable, equitable policy. Smith et al. (2012) and Coulbourne and Miller (2012) demonstrated that institutional buildings such as hospitals and schools experienced significant failures, even when constructed under modern codes [9, 10]. These findings suggested a disconnect between design expectations and actual performance, yet neither study accounted for enforcement inconsistencies or regional policy gaps that may have contributed to these outcomes. Dao et al. (2014) introduced a

variable often absent from engineering-based analyses—building orientation relative to tornado track—indicating that damage patterns are not solely the result of design flaws but also of siting decisions [11]. However, orientation has received limited attention in subsequent building code discussions, revealing an underdeveloped area of inquiry. Prevatt, Coulbourne, et al. (2012) provided one of the most detailed structural assessments of damage in Joplin, identifying roofing system failures as a primary trigger of broader collapse [12]. Their emphasis on cascading structural failure supported calls for improved load path integrity, yet they did not explore barriers to adopting these recommendations. Prevatt, van de Lindt, et al. (2012) extended the focus to include code failure's social and economic consequences, urging a multidisciplinary design paradigm [13]. Their proposal for integrated engineering and social science research marked an important shift; however, it lacked a roadmap for translating such interdisciplinary findings into code reform at the local or state level. Prevatt, Roueche, et al. (2012) and Roueche and Prevatt (2013) both reinforced the argument that non-engineered and poorly connected homes face heightened vulnerability, especially in EF4–EF5 tornadoes [14, 15]. Their emphasis on better anchoring, vertical load paths, and sheathing pointed to actionable retrofit strategies, yet these solutions have not embedded into prevailing building codes.

4.4. Damage and Economic Assessment

The literature on damage and economic assessment following the 2011 Joplin tornado reflects steady advancements in modeling techniques. Yet, limitations remain in model generalizability, integration across infrastructure systems, and adaptation for non-engineered settings. Peng et al. (2016) proposed a detailed damage framework for low-rise, non-engineered structures using a translating vortex model and internal pressure simulations [26]. While the model achieved high accuracy in the Joplin context, its reliance on localized data raises concerns about external validity. Researchers have not adequately tested its applicability in areas with different structural typologies or environmental conditions, leaving a gap in understanding its predictive range. Pilkington et al. (2020) expanded economic impact modeling by incorporating building contents into FEMA HAZUS estimates [27]. Their scenario-based simulations, which altered the tornado's track, underscored the significant influence of commercial structures on loss totals. This work added a needed dimension to traditional models that treat structures as uniform units of damage, though it did not fully consider cascading economic effects, such as long-term business closures or employment disruption. Thomas et al. (2013a, 2013b) advanced post-disaster assessments through high-resolution image classification, demonstrating that automated systems could provide rapid and consistent evaluations of roof damage [28, 29]. These innovations support a shift toward scalable tools in disaster response, but their application remains restricted to surface-level damage. Subsurface structural failure or internal building compromise remains beyond the scope of such imagery, indicating that hybrid systems integrating structural engineering inputs with image-based tools are needed. Attary et al. (2018, 2019, 2020) introduced the IN-CORE framework to model structural and socioeconomic impacts, validating simulations against real-world data from Joplin [30–32]. Their use of interdependent systems modeling, including electric power networks and built environment fragility, represented an important step in assessing compound disaster effects. However, most models assumed static population and infrastructure conditions, which limits the framework's responsiveness to dynamic urban environments where redevelopment or migration may alter risk landscapes. Further, Attary et al. prioritized technical accuracy but did not extend findings to policy translation or equity-focused mitigation strategies. Karstens et al. (2013) added a novel angle to damage analysis through the forensic study of tree fall patterns [33], using them as proxies for wind behavior near the surface. Their work offered insight into tornado mechanics and microbursts, but its relevance for built environment modeling remains indirect. While tree fall orientation helped validate wind field simulations, the practical application of such data in engineering or emergency planning remains limited without integration into existing structural damage frameworks. Across these studies, an evident gap persists in aligning advanced simulation and detection tools with localized policy implementation and diverse structural contexts. Researchers have not yet resolved how high-fidelity modeling systems can inform retrofitting priorities, zoning regulations, or post-event recovery efforts across communities with varied resource levels. Future work must bridge this divide by embedding technical modeling outcomes into decision-making frameworks that account for social vulnerability, infrastructure interdependencies, and changing urban conditions.

4.5. Response and Recovery

The literature on response and recovery after the Joplin tornado offers valuable insights across disciplines but reveals fragmentation and limited cross-study integration. Mason et al. (2017) and Abramson and Culp (2013) addressed early coordination and stakeholder collaboration but did not confront the scalability of such models across communities with fewer resources or less social capital [34, 35]. Smith and Sutter (2013) argued for decentralized recovery processes yet left unexplored how polycentric models perform under structural inequality or without robust civic infrastructure [38]. Paul and Stimers (2015) identified behavioral selectivity in adopting tornado-resistant safety measures [17], highlighting a disconnect between municipal guidance and homeowner response—a gap still underexplored in recovery policy design. Spatial-temporal studies by Pilkington et al. (2021), Stimers and Paul (2022), and Stimers et al. (2022) advanced methodological precision using building permit data [43–45], but these approaches often overlooked intersections with social vulnerability. Their visual and statistical analyses map where rebuilding occurred but do not fully explain in detail why certain areas recovered faster. Similarly, Richmond (2021) and Richmond and Knight (2021) emphasized collaboration and housing stability [41, 42], yet their policy implications remain high-level, without mechanisms for implementation or adaptation in diverse municipal systems. Modeling studies from Wang and van de Lindt (2021) and Aghababaei et al. (2020) refined technical tools for simulating recovery but often treated recovery inputs—like inspections or permit delays—as static, missing the real-world variability captured in permit analyses [6, 49]. Digital innovations such as Nguyen et al. (2015) introduced automated filtering of social media data yet failed to address how emergency managers might realistically adopt and trust these tools alongside legacy systems [39]. Coles et al. (2016) and Grube and Storr (2018) explored interagency and entrepreneurial networks but did not fully connect these with formal policy levers [36, 40]. The literature also lacks sustained attention to long-term inequities. Pilkington and Mahmoud (2021) suggested socio-technical integration but did not resolve how to align such models with localized recovery dynamics [48]. While the response and recovery scholarship on Joplin is rich in empirical detail and methodological innovation, it falls short of producing integrated frameworks that unite behavior, equity, infrastructure, and governance into practical recovery strategies.

4.6. Fatality Studies

Fatality research on the Joplin tornado has produced important findings, yet the field remains constrained by an overreliance on isolated variables rather than integrated causal frameworks. Paul and Stimers (2012) acknowledged the interaction between structural vulnerability, storm intensity, and human behavior, but their conclusions did not resolve how preparedness measures could realistically mitigate fatalities in communities with aging housing stock and limited access to shelter [50]. Although their findings confirmed the role of disbelief and shelter inadequacy, they stopped short of evaluating which behavioral interventions might increase protective action across diverse populations. Curtis and Fagan (2013) introduced spatial video and the Tornado Injury Scale to pinpoint localized mortality risks, showing that damage and death vary sharply within small geographic zones [51]. Their methodological innovation outpaced traditional damage surveys, yet the study did not fully account for how emergency planners might operationalize these tools in real-time. Similarly, Paul and Stimers (2014) disrupted typical assumptions by revealing that most fatalities occurred in nonresidential buildings [52]; this pattern shift raised important questions about risk concentration in commercial areas but went unlinked to policy recommendations on commercial building codes or business preparedness protocols. The elevation-focused analysis by Paul and Stimers (2017) introduced terrain as a new spatial lens, finding that lower elevations correlated with higher fatality rates [53]. While valuable, the explanation remained speculative, pointing to possible associations with older buildings or socioeconomic status without empirically testing those links. Across the fatality studies, researchers have identified important risk patterns—commercial vulnerability, demographic disparities, and topographic variation—but have yet to unify these into predictive models or recovery frameworks that integrate environmental, structural, and social data. A major gap remains in translating granular spatial findings into actionable zoning, sheltering policy, or public education initiatives that could materially reduce future tornado-related deaths.

4.7. Human Health

The human health literature on the Joplin tornado covers a broad range of medical, psychological, and epidemiological concerns yet suffers from fragmentation and insufficient linkage across domains of practice, policy, and community-level outcomes. Avitzur (2011) and Barbe (2012) offered anecdotal and institutional perspectives on medical preparedness and facility recovery [54, 55], yet neither addressed how healthcare professionals could systematize such practices across small and large healthcare networks. While both highlighted improvisation and rapid response as key assets, they provided limited analysis on how those lessons might inform standardized protocols or disaster accreditation benchmarks. Charney et al. (2014) advanced this by quantitatively linking healthcare worker preparedness and willingness to work post-disaster [56], with findings emphasizing childcare as a key constraint. However, the policy implications of that insight—particularly how to support essential personnel with dependent care responsibilities—remain underdeveloped. The psychological and behavioral health research is more robust but similarly siloed. Houston and Franken (2015) and Houston et al. (2015) identified strong links between disaster experience and persistent mental health symptoms but also noted underutilization of services [57, 58]. While the data demonstrate a clear need, researchers did not explore mechanisms to increase uptake, such as culturally relevant outreach or long-term mental health integration into primary care. Studies on narrative processing revealed how trauma is internalized and expressed, particularly among children, yet stopped short of offering implementation strategies for therapeutic models in schools or community programs [58, 66]. First et al. (2018, 2024) provided strong evidence of posttraumatic growth and unmet psychological needs, but their recommendations for more integrated recovery frameworks remain general rather than operationalized [60, 63]. Langan et al. (2017) and Brown (2017) offered insight into demographic and spiritual influences on resilience but failed to account for structural barriers that constrain psychological recovery across communities with fewer resources [4, 59]. Kanter and Abramson (2014) delivered one of the few applied case studies showing how schools can directly support youth mental health through rapid reintegration and targeted support [64]. Yet, that model has not been scaled or evaluated longitudinally, leaving questions about its sustainability. Adams et al. (2015) and Christopher et al. (2019) revealed serious mental health impacts among adolescents and prenatal populations, respectively [65, 67], but their work remains largely diagnostic, with little follow-through on intervention planning or family-based prevention strategies. Infectious disease literature surrounding mucormycosis highlighted a rare but deadly post-disaster risk [68, 69], calling attention to environmental exposures in trauma care. However, their findings remain isolated from the broader disaster health literature, and no formal protocols appear to have emerged linking fungal risk to triage standards or injury surveillance systems. The literature has produced high-quality, topic-specific findings across all subfields—medical preparedness, mental health, epidemiology, and trauma response—but lacks a unifying framework that connects these domains into an interdisciplinary, actionable public health model for post-disaster environments. Opportunities remain to synthesize these strands into comprehensive preparedness, response, and recovery protocols that center on health equity, system interoperability, and long-term resilience.

5. Conclusions

The 2011 Joplin tornado provided a wealth of data and insights into disaster management, resilience, and community recovery. The authors highlighted the elements contributing to vulnerability and resilience by synthesizing research across multiple disciplines in this review. Effective preparedness, safe building practices, clear communication, and community involvement are essential for enhancing resilience and reducing vulnerability to future tornadoes and other natural disasters. The lessons from Joplin offer valuable guidance for policymakers, emergency management officials, and urban planners in developing more effective strategies to protect and rebuild communities in the face of severe weather events.

Author Contributions

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