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The adaptive shift: Embracing complexity in disaster and emergency management

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A R T I C L E I N F O

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A B S T R A C T

Disaster and Emergency Management (DEM) systems are increasingly challenged by the complexity and interconnectedness of today's DEM environment. While rigid, phased-based approaches to DEM provide valuable structural frameworks, they often fail in addressing the dynamic, non-linear, and unpredictable nature of contemporary disasters. This paper critically examines key challenges in DEM, including non-linearity, complexity, and the coordination of diverse actors and organisations. It advocates for a shift towards adaptive, interconnected systems that better align with the realities of complex disasters. To this end, the paper introduces the Complex Adaptive DEM (CADEM) Framework, a new conceptual framework grounded in Complex Adaptive Systems (CAS) theory. This framework emphasises decentralised decision-making, interorganisational collaboration, and emergent behaviours as mechanisms to enhance the adaptability and resilience of DEM systems. By reframing DEM as a networked and adaptive system, CADEM provides a pathway for navigating the multifaceted challenges of contemporary disasters.

1. Introduction

Contemporary Disaster and Emergency Management (DEM) frameworks face significant challenges in capturing the complexity and interconnectedness of today's disasters, as well as accommodating the diversity of actors involved. Rooted in militaristic principles from the total-war era, current DEM practices often rely on hierarchical, linear command structures that struggle to address the multi-layered and dynamic nature of today's disasters [1–3]. There is thus a critical gap between the complexity of disasters and the limited adaptability of DEM systems. This paper argues that more flexible, decentralised and adaptive approaches are needed to deal with the complexity of contemporary disasters [4–6].

The DEM environment has evolved significantly over the last 4–5 decades [7], driven by changing disaster definitions, diversified management approaches, and an expanding spectrum of actors - from governmental agencies to community-led initiatives [8–10]. However, the persistent reliance on military-style command structures has limited DEM's capacity to address complex challenges, where rigid, top-down approaches can impede timely and effective responses [9,11]. In an era of increasingly unpredictable and interconnected disasters, these structures often fail to account for the emergent, non-linear nature of disaster systems, where response effectiveness depends on adaptability and collaboration.

To address the gap, this paper introduces the Complex Adaptive DEM (CADEM) Framework, a conceptual framework informed by

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Complex Adaptive Systems (CAS) theory. Unlike traditional command-and-control structures, which rely on rigid hierarchies and predefined roles, CADEM enables real-time adaptation, self-organisation, and cross-sector collaboration to enhance disaster response effectiveness. By framing DEM as a continuum of interconnected systems, rather than a static, command-driven process, the CADEM Framework provides a flexible, adaptive model that better aligns with the realities of contemporary disasters.

The paper comprises six sections. Section 2 explores the evolution of disaster management, tracing its historical development and highlighting the paradigm shifts that have shaped contemporary practices. Section 3 discusses the progression of DEM frameworks, identifying the increasing need for flexibility and adaptability in addressing the complexities of contemporary disasters. In Section 4, the focus shifts to systems thinking and complexity theory, which provide a foundational lens for understanding DEM as a complex adaptive system. Building on this theoretical groundwork, in Section 5, the paper introduces the CADEM Framework, a novel approach that demonstrates how the principles of CAS can be effectively integrated into DEM to enhance resilience and adaptability. These interconnected yet distinct sections provide a comprehensive exploration of the dynamic and evolving nature of DEM, as concluded in Section 6.

1.1. Methodological approach

This study employs a multi-method approach, combining a comprehensive literature review with theoretical synthesis to develop the CADEM Framework. The research draws on systems thinking, complexity theory, and CAS principles to explore how disaster management structures can become more adaptable and responsive. A comprehensive search strategy was employed to identify key themes related to *interorganisational collaboration, network, complexity theory*, *complex adaptive systems*, *disaster, emergency management,* and *incident command systems*. This review informed the conceptual development of the CADEM Framework by synthesising insights from disaster studies, organisational theory, and network governance. The review process also helped identify gaps in existing DEM models and validate the need for a CAS-informed framework.

To ensure methodological rigour, academic databases such as Scopus, EBSCO, and Google Scholar were searched using targeted keywords and Boolean operators (such as AND, OR, and NOT) to focus on the relevant literature. Peer-reviewed journal articles, conference proceedings, and seminal texts were prioritised with exclusion criteria filtering out outdated, non-peer-reviewed, studies published prior to 2010 (unless foundational), or irrelevant sources. Additionally, backward and forward citation tracking was conducted to incorporate both foundational works and emerging perspectives.

This paper employs theoretical synthesis as a methodological approach [12], integrating insights from complexity and disaster management to develop the CADEM Framework. This conceptual model was refined through an iterative process, drawing on existing CAS frameworks and their applicability to DEM structures. By bridging theory and practice, this paper aims to provide a practical, adaptable framework for managing the increasing complexity of disasters.

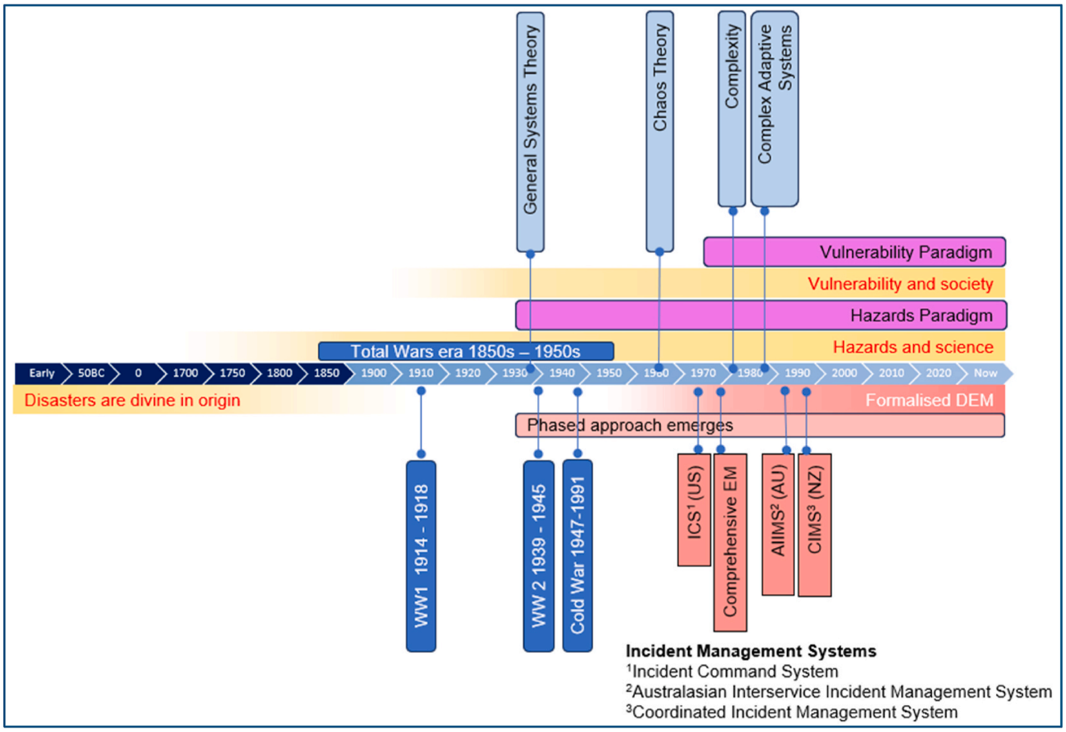

Fig. 1. Timeline of DEM transformation.

2. The evolution of disaster management

The historical evolution of DEM underscores the field's need for adaptive, flexible, and inclusive approaches to address the complexities of today's disaster environment [9]. Contemporary disasters are marked by greater complexity, scale, and unpredictability [13,14]. Events are no longer limited to natural hazards, such as earthquakes, floods, or hurricanes; they increasingly encompass technological failures, pandemics, cyber-attacks, and cascading disasters, where one event triggers or intensifies another [15]. Additionally, the global interconnectivity of systems - spanning supply chains, communication networks, and transportation - means that disasters can now produce extensive and unforeseen consequences across borders, impacting multiple sectors at once [16]. The enduring influence of military principles on DEM further shapes its foundational practices, intersecting with evolving societal factors and shaping the field's responses to contemporary challenges [17,18].

2.1. Historical evolution of DEM

The evolution of DEM (Fig. 1) reveals its strong historical ties to military principles, reflected in the continued use of phased approaches and hierarchical frameworks. The Enlightenment era marked a significant shift from viewing disasters as divine punishments to understanding them as natural phenomena [19]. This scientific perspective, initially spurred by events such as the 1755 Lisbon earthquake within the context of western society, laid the groundwork for modern hazard-focused disciplines like seismology and geology [20,21], with its influence gradually increasing wider over time. The total-war era (mid-19th to mid-20th century) significantly shaped organised societal responses to crises, for example, the comprehensive mobilisation of resources which blurred distinctions between military and civilian roles [22], and introduced innovations in logistics and communication [23,24]. However, these approaches have been critiqued for their Eurocentric focus, often overlooking the distinct needs of diverse global regions [25–29]. By the early 20th century, the hazard paradigm emerged, framing disasters as natural events exacerbated by human unpreparedness. This paradigm which underpins many current DEM practices, prioritises technical solutions and command-and-control strategies but has been criticised for its narrow focus and inability to address the complex social dynamics of disasters [25–28].

The recognition of multi-disciplinary approaches in DEM emerged in the mid-1960s, an era shaped by significant human-induced geological impacts and the height of nuclear testing [20,30]. The early 20th century's hazard paradigm, focusing on scientific interpretations of hazards, gradually expanded to incorporate broader disciplinary perspectives and knowledge domains, acknowledging the complex interplay of physical and social dimensions in disasters. This shift marked a departure from the hazard paradigm's narrow focus on scientific interpretations of hazards, which often oversimplify disaster complexities and overlook socio-economic, political, cultural, and historical factors that influence vulnerability [31,32].

The emergence of the vulnerability paradigm reframed disasters as outcomes of both extreme physical phenomena and the underlying societal conditions that exacerbate human vulnerability [33]. This perspective emphasised how disparities in resource distribution, governance structures, and systemic inequalities contribute to differential disaster vulnerabilities across and within societal groups [34]. The integration of multi-disciplinary approaches has been central to advancing this paradigm [20], enabling a more comprehensive understanding of how vulnerability is produced and sustained. For example, insights from social sciences help analyse socio-economic inequalities and marginalisation [35], while urban planning and geography contribute to identifying spatial vulnerabilities and infrastructure deficiencies [36]. Similarly, public health and epidemiology provide critical perspectives on the disproportionate impacts of disasters on health systems and at-risk populations [37], while political science and governance studies illuminate the power dynamics that shape disaster response and recovery [38].

Dominey-Howes [20] emphasises that adopting a multi-disciplinary approach not only broadens perspectives essential for managing disasters but also increases the complexity of interorganisational collaboration, making the understanding of social vulnerabilities a cornerstone of contemporary DEM [26]. While integrating societal factors into DEM introduces challenges - such as the need for greater coordination across agencies and the allocation of additional resources - it also enhances the effectiveness and equity of disaster strategies. Addressing the diverse needs and capacities of communities ensures that policies and interventions do not simply mitigate immediate risks but also tackle the systemic vulnerabilities that perpetuate disaster exposure [39,40].

Lessons from past disasters reinforce the necessity of adopting comprehensive, multi-disciplinary approaches to DEM, particularly in addressing social vulnerabilities and fostering interorganisational collaboration. The 2023 weather events in New Zealand, as examined by the Government Inquiry into the Response to the North Island Severe Weather Events [6], highlight the importance of multi-disciplinary approaches in reducing vulnerability. Evidence from this inquiry demonstrated that regions with established mechanisms for active community participation rooted in social coordination, governance, and indigenous knowledge – were better equipped to manage the crisis. This underscores that integrating marginalised and vulnerable groups into DEM policies and practices is not merely an ethical imperative but also a practical necessity to ensure more inclusive, equitable and effective disaster risk reduction [41,42].

2.2. The influence of military principles in DEM

The longstanding association of DEM with military principles continues to be evident today - as highlighted in later discussions on incident command systems (ICS) - characterised by a well-defined hierarchy of authority [43] and the development of ICS. Buck and Trainor [44], and Hodges and Larra [9] critique these systems as poorly suited to the complexity of contemporary disasters, with enhanced collaborative approaches to mitigation, response, and recovery required. A key critique of military-influenced frameworks is their emphasis on operational efficiency, often at the expense of inclusivity [45]. These systems tend to prioritise formal actors such as government agencies and emergency services, while marginalising the contributions of local communities, non-governmental organisations, and informal actors [46,47]. This limited focus overlooks the critical role these groups play in providing local knowledge, resources, and support during a disaster [13,41]. Consequently, these frameworks highlight the need for a broader exploration of actor inclusion and the development of more comprehensive engagement strategies to ensure more effective disaster response and recovery [48].

Furthermore, military-style systems may struggle to incorporate the complex social dynamics that shape disaster outcomes [49]. Disasters are not just physical events; they are also social events, and their impacts are deeply influenced by factors such as inequality, poverty, and marginalisation [50]. Command and control structures, which are primarily concerned with operational tasks, may overlook these social dimensions, leading to disaster responses that are technically efficient but socially ineffective [1,45]. For example, in the aftermath of Hurricane Katrina, the command structure focused heavily on search and rescue operations but failed to adequately address the needs of vulnerable populations, such as low-income communities and people with disabilities, who were disproportionately affected by the disaster [11]. Similarly, during the Auckland floods of January 2023, the response prioritised immediate operational goals, such as infrastructure repairs and evacuation logistics, but was criticised for failing to adequately engage with local communities and vulnerable groups, leaving gaps in addressing their specific needs and fostering long-term recovery [51].

3. Evolving DEM frameworks and the need for flexibility

The phased approach to disaster management has provided a foundational framework for structuring DEM practices [52,53]. However, as disasters grow more complex and interconnected, this approach faces criticism for its rigidity. This section explores its origins, strengths, and limitations, emphasising the need for more adaptive and integrative models.

3.1. *The phased approach to disaster management*

The development of emergency management frameworks has been integral to structuring and guiding DEM practices [54]. The phased approach used today is rooted in the early work of Carr [55] which delineated disasters into a clear and distinct set of phases: 1) a precipitating event or condition; 2) adjustment-dislocation; and 3) individual, interactive, and cultural readjustments [13]. Comprehensive Emergency Management (CEM), which further refined Carr's model, was introduced in the United States in 1979 and marked a significant development in structuring DEM. CEM identified four phases: mitigation, preparedness, response, and recovery (MPRR) [56]. While CEM has remained influential, it has been adapted to reflect national and contextual differences, such as Australia's prevention, preparedness, response, and recovery (PPRR) [57], and New Zealand's (risk) reduction, readiness, response, and recovery (4Rs) (MCDEM, 2009). It is also important to acknowledge that DEM frameworks are still evolving and will likely continue to exhibit national and regional variations for some time [7]. Moreover, countries outside the US, Australia and New Zealand utilise alternative approaches tailored to their unique socio-political and hazard environments [59,60], reflecting the diverse needs and priorities in global DEM practices. These variations underscore the ongoing development of disaster management as a field, adapting to the complexities and demands of contemporary disaster contexts.

Despite the country-specific adaptations, scholars have critiqued the phased approach for not adequately acknowledging the overlapping and complex nature of DEM [50,54]. Neal [54] argues that although the use of disaster phases may assist organisations in orienting themselves and placing disasters temporally in space and time, the approach can also be limiting. This is because disaster phases are mutually inclusive and multidimensional [13]. For example, the 2011 Tōhoku Earthquake and Tsunami in Japan triggered a sequence of events, including the Fukushima Nuclear disaster. Managing such complexity required an adaptive approach that transcended traditional phased perspectives the interconnected nature of cascading events, such as the simultaneous need for immediate response to the tsunami, ongoing crisis management at the Fukushima Nuclear plant, and the longer-term recovery of affected communities. These overlapping demands required a fluid and adaptive approach that could address multiple disaster phases concurrently, highlighting the inadequacy of traditional phased frameworks in managing such multifaceted crises [61].

McEntire [62] highlights that while CEM begins to recognise the importance of collaboration, its focus is predominantly on those actors formally involved in the phased approach to hazard mitigation. This includes agencies and organisations responsible for disaster response and recovery at the federal, state, and local government levels [63]. By focusing on these institutional players, CEM seeks to streamline coordination and operational efficiency across the disaster management cycle.

The foundational phased approach has been critiqued for not fully recognising the complexity of compounding events which are characterised by the interaction of multiple hazards that exacerbate the overall impact of a disaster [13,64], such as the simultaneous emergence of a pandemic, extreme weather event, and earthquake, either concurrently or in close succession. The phased approach is also critiqued for not adequately addressing cascading and compounding events, which encompass both the amplification of initial disasters and the emergence of subsidiary disasters [15]. Cascading and compounding events can create complex feedback loops that overwhelm traditional response mechanisms, highlighting the need for more adaptive and integrative frameworks capable of addressing the dynamic and multifaceted nature of disasters, while also accounting for the prolonged duration of societal recovery efforts [65].

The contrast between two significant US hurricanes, the 1935 Labor Day Hurricane and Hurricane Harvey in 2017 exemplifies the evolving complexity of disasters and the corresponding challenges in DEM. The Labor Day Hurricane, though catastrophic, primarily affected a sparsely populated area with limited infrastructure, and its impact was largely confined to the immediate aftermath of the event [66]. In contrast, Hurricane Harvey demonstrated the multifaceted nature of contemporary disasters, where prolonged flooding, urban sprawl, and interconnected critical systems significantly amplified the scope of the emergency [67,68]. Harvey's cascading effects, from socio-economic disruptions to technological and infrastructural failures, illustrate how contemporary disasters transcend traditional response paradigms, demanding a more dynamic and adaptive approach to DEM that incorporates systemic interdependencies and long-term resilience planning [69].

The development and critique of emergency management frameworks highlight the ongoing evolution of the DEM field [13]. While structured methodologies like CEM and the phased approach have provided valuable foundations, such as guiding doctrinal development and response strategies [70], their limitations in addressing the intricacies of contemporary disasters demand a fundamental rethinking of how the disaster continuum is conceptualised.

3.2. Are current incident command systems too rigid for contemporary disasters?

The development of incident command systems – many of which have a military heritage, adopting hierarchical command-and-control principles [71] - such as the US Incident Command System (ICS), the Australasian Inter-service Incident Management System (AIIMS), the New Zealand Coordinated Incident Management System (CIMS), and the UN Cluster system have attempted to systemise the coordination of various organisations during emergencies, however, these systems often embody rigid protocols that may conflict with the agility required by contemporary disasters [44]. This tension highlights the need for a balance between structured incident management and the flexibility to adapt to rapidly changing circumstances [72].

Critiques of the mainly westernised systems focus on their rigid structures, which may not be agile enough to adapt to novel problems and dynamic disaster environments or foster collaboration with emerging and novel actors [1,51,73,74]. Andrew's [75] critique of the Black Saturday Fires in Australia identified that the established ICS failed to adapt to the highly dynamic and complex environment of the catastrophic wildfire, with the networked connectedness being suboptimal, resulting in an inefficient response. The Black Saturday fires underscore the critical need to re-evaluate incident command frameworks, particularly their ability to accommodate high levels of complexity and uncertainty in disaster scenarios. In this case, the rigidity of the ICS limited situational awareness and hindered the coordination necessary for managing cascading events, suggesting that more flexible, decentralised structures could improve outcomes in dynamic environments.

3.3. Organisational and legislative adaptability in DEM

Organisational culture and structure are pivotal in mediating the balance between agility and traditional rigidity in DEM systems [76]. The work of Jensen and Youngs [77] underscores the importance of interorganisational attributes in the implementation of the US National Incident Management System (NIMS), revealing how cultural factors can either facilitate or hinder the effective integration of incident management processes. Their findings suggest that fostering a culture of collaboration and adaptability is essential for enhancing the resilience and efficacy of DEM systems. Additionally, adaptable organisational structures are critical, both at systemic and sub-system levels, to align diverse actors with common objectives under time and resource constraints [78]. Viewing incident command systems within the broader context of complexity and network theory offers insights into interdependencies and emergent behaviours, further underscoring the need for flexible organisational practices [9,17,79].

Equally important is the role of legislation in supporting the effectiveness and adaptability of DEM systems. Legislative frameworks provide the foundation for addressing systemic challenges and fostering interorganisational coordination. The withdrawal of New Zealand's Emergency Management Bill in 2024, prompted by inadequacies exposed during the response to the North Island Severe Weather Event, illustrates the critical need for reform. The event highlighted the system's lack of capacity to address significant disasters, driving calls for legislative changes to improve interagency collaboration, adopt multi-disciplinary approaches, and include a wider range of stakeholders [80–82].

Together, organisational adaptability and legislative enablement form the backbone of a resilient DEM system. By integrating adaptive cultural practices and robust legal frameworks, DEM systems can better address the complexities and interdependencies inherent in contemporary disasters.

3.4. Limitations of traditional DEM frameworks

Disaster management frameworks often rely on hierarchical structures and standard operating procedures which can lead to inflexibility and delays in responding to the dynamic and uncertain environments inherent in disasters [1,83]. This rigid approach often overlooks the importance of local knowledge and community capacity in disaster management [73]. Traditional frameworks tend to prioritise response and recovery over mitigation and prevention [83,84] and frequently encounter challenges in effective communication and coordination among multiple agencies and stakeholders. In contrast, Tacheva and Simpson [85] highlight one of the main benefits of the UN cluster approach is "to provide a platform for communication between agencies" (p.501), facilitating greater coordination and information sharing.

Traditional DEM frameworks face additional challenges when applied to contemporary disasters, which are increasingly characterised by their complexity, driven by multifaceted factors such as climate change, urbanisation, and growing social inequalities [86,87]. These factors amplify the scale of disasters, intensifying their frequency, geographic reach, and societal impact, while also exacerbating vulnerabilities and stretching existing response capacities beyond their limits. As a result, such events pose significant challenges to existing DEM approaches, which have historically relied on simplified, event-focused models [88]. The limitations of these approaches are evident in their tendency to oversimplify disaster risk, neglect the root causes of vulnerabilities, and exclude local communities from the planning and response process. Jha [89] highlights that those most vulnerable are often systematically excluded from disaster planning, response, and recovery efforts. This exclusion stems from entrenched social vulnerabilities shaped by intersecting factors such as caste, gender, age, and socio-economic status. However, this narrow focus often marginalises vulnerable and affected communities, whose perspectives and needs are critical but frequently overlooked [13,31]. These groups, who do not experience or recover from disasters uniformly or at the same pace, are rarely given a voice in the design and implementation of disaster strategies [62]. To create a truly inclusive and effective framework, it is essential to integrate their diverse experiences, recognising that community participation is vital for building resilience and ensuring equitable recovery [90].

3.5. Conceptual gaps and future directions for DEM

One of the significant gaps in existing disaster management frameworks is their reliance on linear models, such as the "disaster cycle," which fail to account for the complex, interconnected nature of modern disaster risk [13,91]. Many frameworks continue to view disasters as isolated events rather than the result of long-term socio-economic and political processes [91,92]. This oversimplification results in a failure to address root causes, such as systemic inequalities, which contribute to repeated cycles of vulnerability [91]. Furthermore, DEM approaches that focus primarily on response and recovery often overlook the need to address these underlying factors, perpetuating the risk of future disasters [83]. The failure of “building back better” initiatives to achieve meaningful systemic change has been particularly criticised for reinforcing existing social and economic disparities [93].

In addition to these conceptual gaps, traditional disaster management frameworks are hindered by limitations in community engagement and information management [9]. The top-down nature of disaster response often excludes local populations, depriving decision-makers of valuable local knowledge and perspectives that could enhance resilience [94]. Moreover, existing systems for knowledge management frequently struggle to gather, process, and disseminate necessary data during crises, which impedes timely decision-making [95]. The unpredictable and cascading nature of contemporary disasters further compound these challenges, where one event can trigger a series of consequences across sectors and regions, amplifying the overall impact. To address these gaps, DEM must evolve towards more dynamic and inclusive approaches, incorporating real-time information systems, building social capital, strengthening community networks beyond the formal government/response agency perspective to foster greater collaboration and resilience.

4. System thinking and complexity

DEM increasingly views disasters as complex phenomena shaped by dynamic, interdependent systems. Applying Complex Adaptive Systems (CAS) principles highlights the need for a balance between centralised coordination and decentralised flexibility, enabling adaptive, collaborative, and resilient disaster responses.

4.1. Theoretical foundation

The emergence of CAS as a prominent concept occurred in the latter part of the 20th century, informed by foundational principles spanning diverse disciplines, including biology, physics, and mathematics [18,72,96,97]. The Santa Fe Institute was instrumental in pioneering CAS research with scholars concentrating on the interactions among a system’s individual elements to create a collective, coherent whole [18,72]. The concept was to explain how rudimentary rules could give rise to complex behaviours and how systems could adapt to changing environments. As an example, this may be seen in community-led responses, where simple directives such as *“shelter in place”* or *“evacuate to higher ground”*, when followed by individuals and local communities, often lead to complex adaptive behaviours. As these networks interact, the collective actions of individuals evolve into a self-organised system capable of adapting to unforeseen challenges [98].

Ahmed [16] adds another layer of complexity to the understanding of CAS by stating that these systems are "composed of multiple interacting agents" (p.22). In this context, ’agents’ refer to the individual components or entities within the system that interact with each other and their environment. These interactions are not merely additive but often result in emergent properties, meaning that the system’s overall behaviour cannot be easily predicted by examining its individual parts. These networks consist of multiple interacting agents—such as first responders, governmental agencies, and community organisations—that collaborate and adapt in real-time during a crisis [99]. Although protocols and procedures guide the interactions among these agents, understanding the network’s overall effectiveness in managing a disaster as an emergent property requires more than examining each agent in isolation [100].

The evolving DEM perspectives detailed in section 3, which increasingly have come to perceive disasters as multifaceted entities shaped by intricate technical and environmental interactions [13,101], developed in parallel with the emergence of General Systems Theory (GST) in the 1930s [101]. Proposed by Von Bertalanffy [102], GST was a counterpoint to the reductionist approach of science, advocating for a holistic view of systems. This theory posited that the interplay between different components of a system results in emergent properties not seen when analysing the parts in isolation [103]. However, GST has been critiqued for oversimplifying complexity and failing to provide robust foundational principles. Scholars such as Morin [104], Baker and Turner [79], and Mainzer [105] highlight that GST often lacks the ability to capture the dynamic and interdependent behaviours of real-world systems. Specifically, Morin argues that GST failed to establish its own foundational principles and tends to simplify itself. Morin [104] reflects on this by highlighting the historical recognition of systems in defining complex interrelations and criticises the singular focus of holism as limited and not fully multidimensional (p.372). Citing Pascal’s 1888 [106] observation that it is "impossible to know the parts, without knowing the whole, or to know the whole, without knowing the parts", Morin [104] explores the interdependent nature of this relationship suggesting that the paradox of mutual exclusivity between the parts and the whole is resolved through recognising and exploring their interdependence, proposing that genuine comprehension arises from navigating this complexity. In a disaster context, this perspective highlights the need to understand both the individual actors such as agencies, NGOs, and communities, and the broader system they comprise. Effective DEM requires recognising the interdependence between these parts and the whole, as the complexity of disasters emerges from the dynamic interactions within the system.

The complexity paradigm arose to “better describe and understand dynamics and processes of change” [107]. In this paradigm, each part of the system holds a dual identity: it is both an individual component and an integral part of the whole. These parts are characterised by internal diversity, which Morin [104] argues arises from their unity. This internal diversity, in turn, contributes to the unity of the system [108], creating a feedback loop between diversity and unity. Morin [104] also posits that systems inherently contain conflicts and "forces that are antagonistic to their own perpetuation” (p.375). This idea introduces another layer of complexity, termed ‘unitas multiplex’, which suggests that systems are complex entities made up of multiple, often conflicting, components. According to Morin, Holism overlooks two crucial aspects: interactions and organisation. The components of a system are not isolated; they are the result of complex interactions between smaller units that constitute them, providing protection, regulation, and governance of the system through their interwoven relationship.

As the concept of CAS evolved, its principles began to be applied to organisational theory [105]. Organisations were seen as complex systems with interdependent parts that could adapt to changes in their environment [109]. The understanding of organisations as CAS allowed scholars to examine how localised interactions within an organisation could lead to emergent global patterns, thereby offering fresh insights into organisational learning, innovation, and adaptability [109,110]. For example, an early implicit application of CAS in DEM can be observed in the response to Hurricane Katrina in 2005. Though the interorganisational coordination and government response has been critiqued as being sub-optimal [70,111], this large-scale disaster underscored the necessity of a systems approach that recognises the complexity, unpredictability, and adaptive nature of emergencies. Although not explicitly identified as CAS at the time, the principles of CAS were intrinsic in the shift towards understanding and managing disasters.

The applicability and generalisability of CAS across disciplines also face scrutiny. Although CAS principles have been extended to diverse fields—from ecology to economics—some caution against overextending the framework, advocating instead for a more focused, context-specific application [96,112]. Establishing universal principles to guide CAS behaviour across domains remains an ongoing challenge, limiting the extent to which insights from one CAS context can inform another [14]. When human actors are introduced, the modelling difficulties increase, as individual cognitive processes and decision-making behaviours complicate the system’s dynamics [14,112]. Understanding how individual choices both influence and are influenced by the larger system adds an extra layer of complexity, necessitating further research to integrate human factors effectively into CAS models.

4.2. Integration of CAS into DEM

In the context of DEM systems, the insights from complexity theory and Morin’s critiques provide valuable perspectives om understanding and managing disaster environments. DEM systems are inherently complex and demand coordination and adaptability to respond effectively to changing circumstances [69]. Viewing these systems through the lens of complexity theory offers a nuanced approach that recognises the dual identities of individual organisations as both independent entities and integral parts of a larger, interconnected system. This perspective underscores the significance of internal diversity within organisations and the broader system [113], as well as the inherent conflicts and external stressors that contribute to the overall complexity.

Turner and Baker [79] identify CAS as a useful lens for understanding and applying complexity theory in systems operating within dynamic and evolving environments. The elements of CAS encompass complexity, agents, adaptation, feedback, emergence, and self-organisation [18]. Rooted in chaos theory and evolutionary biology, the CAS approach emphasises non-linearity, feedback loops, and emergent properties [16]. It is situated within the broader paradigm of Morin’s complexity theory [104,105], which provide a multidimensional understanding of interconnected systems.

A distinguishing feature of CAS is its decentralised nature, characterised by numerous dispersed, interrelated components that operate without substantial centralised control [97]. However, in the context of DEM systems, some level of centralised coordination remains essential to provide strategic oversight and ensure coherence across diverse efforts. This centralised role should not stifle localised decision-making but rather facilitate semi-autonomous actions by individual components within the system. By striking a balance between centralised coordination and decentralised adaptability, DEM systems can leverage the strengths of CAS principles while maintaining the necessary structure to respond effectively to complex and evolving disaster scenarios.

Researchers and practitioners in DEM have increasingly focused on the dynamic, non-linear interactions among diverse entities, such as government agencies coordinating evacuation plans with local councils, NGOs providing emergency shelters, and community groups disseminating real-time information during crises [11,114]. These interactions align with the principles of CAS, moving beyond linear, top-down models to more adaptive, networked approaches [9]. For instance, during a flood, feedback loops between weather services, emergency responders, and affected communities enable continuous adjustments in resource allocation and evacuation routes. Such feedback-driven processes illustrate how the decentralised nature of CAS allows emergent properties, like the spontaneous formation of volunteer networks or the rapid reorganisation of supply chains, to arise from localised actions [115,116].

This practical application of CAS principles reinforces the idea that DEM systems can achieve greater flexibility and adaptability by balancing centralised oversight with decentralised, semi-autonomous actions. Viewing these entities as part of an interconnected CAS highlights how collaboration among diverse actors, driven by emergent behaviours and localised decision-making, can lead to improved coordination and more effective disaster response strategies [9,75]. By adopting this perspective, DEM systems are better equipped to respond to the complexities of contemporary disasters, where rapid adaptation and interdependent actions are crucial.

The application of complexity theory and CAS principles to DEM highlights critical gaps in traditional frameworks, reinforcing the need for adaptive, networked approaches. As outlined in Fig. 2, evolving influences on DEM underscore the limitations of rigid, hierarchical models and the growing necessity for interdisciplinary, flexible approaches. These constraints hinder the ability to manage contemporary disasters, which are increasingly characterised by non-linearity, emergent risks, and cross-sector dependencies. Key insights reveal that disaster responses are most effective when they embrace decentralised coordination, self-organisation, and feedback-driven adaptation. Additionally, integrating local knowledge and informal networks into disaster governance structures enhances system resilience and responsiveness. These findings underscore the imperative for a paradigm shift in DEM, moving beyond static, phase-based models toward dynamic, adaptive systems that align with the principles of CAS. Building on these insights, the next section introduces the Complex Adaptive DEM (CADEM) Framework, a conceptual framework designed to operationalise CAS principles within DEM, fostering a more flexible and resilient approach to disaster response and recovery.

4.3. Complex adaptive DEM

The Complex Adaptive DEM (CADEM) Framework (Fig. 3) is a conceptual framework designed to operationalise CAS principles within DEM. Traditional models, which rely on rigid hierarchies and linear coordination, often fail to adapt to the fluid and evolving nature of disasters, limiting effective response. This framework reconfigures DEM as a dynamic, networked system that fosters real-time adaptation, decentralised decision-making, and interorganisational collaboration. By integrating structured coordination with emergent, self-organising mechanisms, the framework enhances resilience by ensuring that disaster response efforts remain flexible, distributed, and responsive to complex, evolving challenges.

The CADEM Framework directly addresses key limitations of traditional DEM approaches in three critical ways: (1) it replaces rigid, top-down command structures with adaptive, decentralised coordination; (2) it shifts from static planning models to real-time, networked problem-solving that evolves based on emerging needs; and (3) it prioritises diversity and redundancy to prevent single points of failure and enhance system-wide resilience. Unlike traditional response models that struggle with unanticipated disruptions, the framework embeds continuous learning and feedback loops, enabling the system to evolve as crises unfold.

Dynamic interactions between organisations enable the system to respond effectively to both internal changes, such as resourcing, mandates, and relationships, as well as external stressors, including climate adaptation, economic fluctuations, and political shifts (e.g., local or central government elections). Diversity within the system enhances adaptability, as varied perspectives and capabilities strengthen resilience [117].

The 2010–2011 Canterbury Earthquake sequence provides an applied example of key CADEM principles in action. Rather than relying solely on top-down coordination, response efforts were driven by decentralised, adaptive networks that formed dynamically as new challenges emerged. The Student Volunteer Army (SVA) exemplified self-organising behaviour, rapidly mobilising resources and personnel in ways that complemented and strengthened formal response structures [118]. The presence of multiple, overlapping networks - including government agencies, community-led initiatives, and international responders - illustrates how the framework's emphasis on redundancy, collaboration, and distributed leadership enhances resilience by ensuring that no single failure point cripples the overall response system.

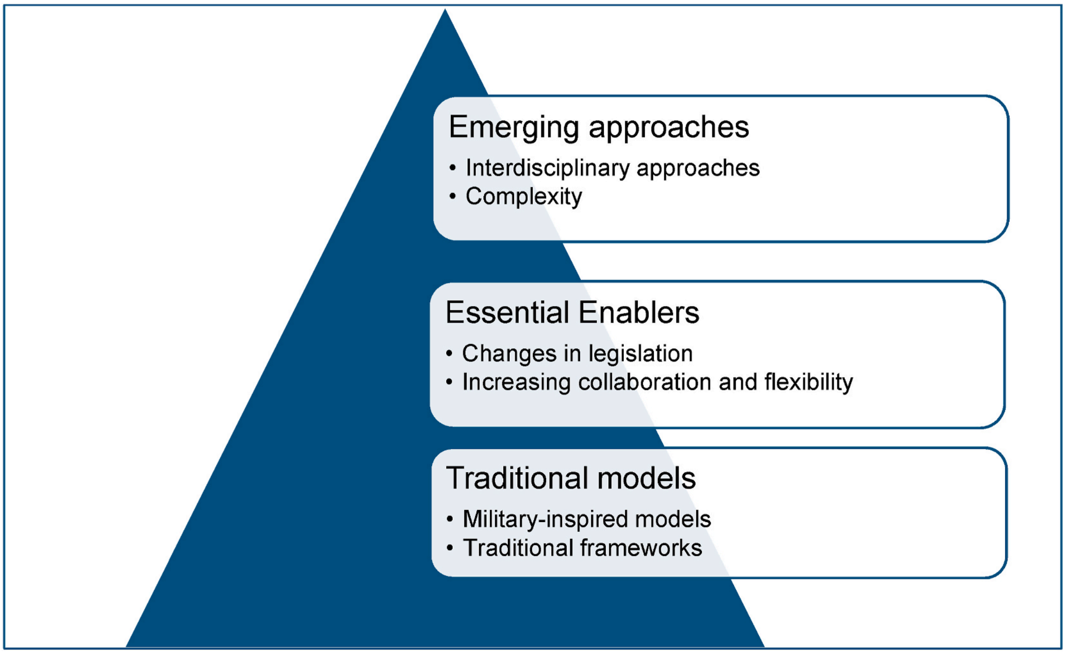

Fig. 2. Key drivers of change in DEM

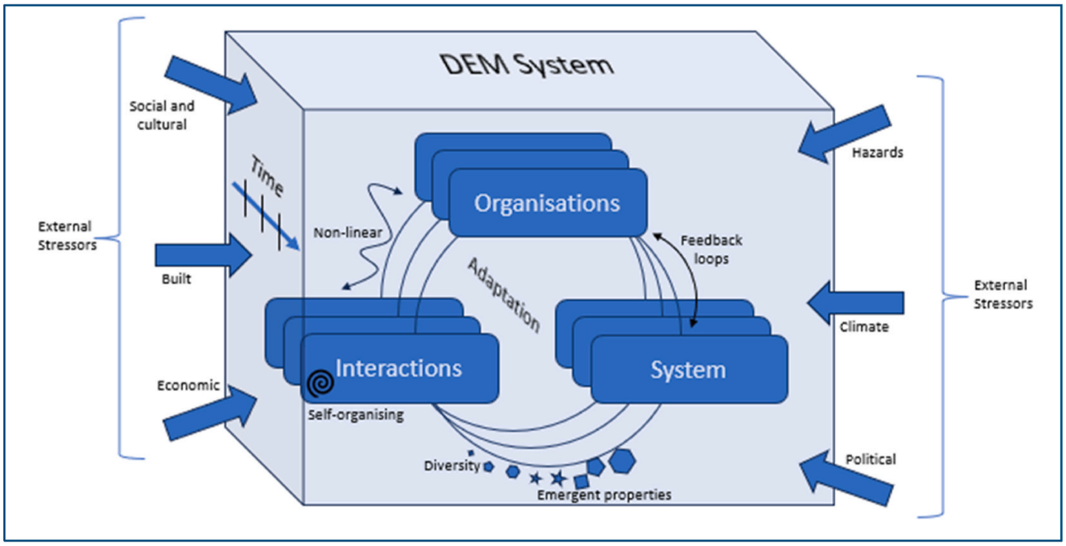

Fig. 3. Complex adaptive DEM (CADEM) framework.

The system's emergent properties, such as collective decision-making, arise from interactions among diverse actors rather than being pre-designed. These interactions enable self-organisation, allowing for the system to function effectively under stress without requiring centralised leadership [119]. Rather than relying solely on predefined roles and procedures, adaptive networks dynamically form in response to evolving crises, enabling rapid coordination and problem-solving through flexible, decentralised collaboration. For example, in the immediate aftermath of the 2004 Indonesian tsunami, local NGOs rapidly mobilised to provide aid. They leveraged pre-existing community networks to coordinate shelter, medical assistance, and resource distribution [120].

Decision-making is distributed across networks, allowing various actors to contribute their expertise and situational awareness. This process helps to generate contextually appropriate solutions. This flexibility enhances resilience, ensuring that the system remains functional even when formal command structures are overwhelmed or disrupted. Additionally, emergent coordination fosters innovation, as diverse perspectives contribute novel approaches to complex challenges. Such adaptability is essential in large-scale or protracted disasters, where evolving needs and cascading impacts demand continuous reconfiguration of response efforts.

Self-organising behaviour, driven by localised decision-making and feedback loops, ensures that the system can reconfigure itself in response to changing conditions over time [121]. This adaptive process is essential for the system to evolve and improve its capabilities, demonstrating the critical role of adaptation in achieving long-term resilience. By incorporating these elements, The CADEM Framework offers a holistic and flexible approach to managing the inherent uncertainty and complexity of disaster environments, positioning itself as an ideal solution for modern DEM challenges.

Community-Based Disaster Risk Management (CBDRM) in Semarang, Indonesia, further validates the principles embedded in the CADEM Framework [116:3]. By empowering grassroots organisations to drive disaster risk reduction, CBDRM demonstrates how locally driven, adaptive networks can increase resilience and ensure that disaster preparedness and response strategies are informed by context-specific knowledge. This aligns with the framework's emphasis on decentralised decision-making, community-led coordination, and the integration of diverse knowledge systems, reinforcing its applicability to complex, real-world disaster environments.

5. Applicability of the CADEM framework

The CADEM Framework underscores the importance of interorganisational collaboration, where diverse actors adapt and learn through shared interactions. By fostering collective efforts and bridging organisational divides, the framework enhances resilience and adaptability in disaster responses. It leverages principles like self-organisation, emergent behaviour, and feedback loops to align efforts and overcome cultural and procedural barriers, enabling a cohesive and integrated response to the complexities of disaster environments.

5.1. Promoting collaboration and emergent adaptability

Interorganisational collaboration, characterised by the dynamic interplay of learning and adaptation among organisations as they respond to changes within their shared environment [105,122], is a central element of the CADEM Framework. This framework brings together multiple autonomous organisations to engage in collective efforts towards common goals [94,123,124], emphasising system adaptability and resilience as fundamental components of disaster management.

Traditional DEM frameworks often rely on rigid structures that may suppress emergent behaviours. In contrast, CADEM prioritises self-organisation, feedback loops, and the interplay of diverse actors to promote system resilience and adaptability. This ensures that even in the absence of centralised coordination, self-organising actors operate within a shared framework capable of adjusting evolving circumstances [125]. The impact of such collaboration is evident in improved disaster response capabilities [69], where collective efforts lead to more robust and resilient outcomes [112].

For example, during the 2015 Nepal earthquake, the community's response demonstrated effective ground-level collaboration and adaptive problem-solving between actors [126], helping minimise subsequent impacts despite gaps in national coordination [127]. Understanding how simple tenets and local interactions lead to complex, emergent behaviours enable DEM professionals to develop strategies that promote consistency and unity across organisations [58]. Such strategies are crucial throughout the disaster lifecycle, where self-organisation and system-wide adaptability allow diverse participants, including emergent groups, to effectively contribute to relief efforts [128,129].

5.2. Challenges and opportunities in applying the CADEM framework

While the CADEM Framework offers a flexible and adaptive approach, its application introduces practical challenges. Transitioning from a traditional, two-dimensional "flat" phased approach to a CAS-based framework introduces additional complexity, making it harder to develop predetermined response models [113]. Balancing organisational autonomy with the necessity for coordinated action requires careful attention to the design and governance of collaborative efforts [130,131].

One of the key strengths of the CADEM Framework is its ability to enhance resilience through emergent adaptation. By recognising non-linear feedback loops and emergent problem-solving, the framework allows DEM systems to anticipate, adapt to, and recover from complex disaster scenarios more effectively than traditional hierarchical models. However, differing organisational cultures, operational procedures, and sectoral priorities can lead to inefficiencies and gaps in coordination. Wicked problems [132], such as the global response to the COVID-19 Pandemic [133], and the response the 2011 Christchurch Earthquake [134,135] highlight these limitations, demonstrating the need for more fluid and adaptive disaster management approaches.

Although CAS principles enhance DEM adaptability, significant theoretical and practical challenges remain. Foundational definitions of CAS lack consensus, leading to variable interpretations of key concepts like adaptation, emergence, and non-linearity across studies [16,18,112,136]. This ambiguity complicates the development of a cohesive CAS framework. For example, the distinction between adaptation and adaptive behaviour is often blurred [72]. Despite these challenges, the CADEM Framework provides a pathway for overcoming these limitations, reinforcing the need for interdisciplinary, flexible, and self-organising approaches in DEM.

6. Conclusion

The persistent tension within DEM between traditional hierarchical models and the emerging need for flexible, adaptive frameworks reflects the evolving challenges of contemporary disasters. Rooted in military command-and-control principles, traditional approaches have shaped foundational DEM practices but struggle to manage the increasing complexity of modern disaster scenarios. The rigidity of phased and hierarchical frameworks often results in delayed responses, inflexibility, and the underutilisation of local knowledge and community capacities. As disasters grow more interconnected and cascading in nature, these limitations underscore the urgent need for a transformative framework that accommodates complexity and promotes resilience across all levels of DEM systems.

The increasing complexity of disasters highlights the necessity for interdisciplinary approaches that integrate social, economic, and cultural dimensions into disaster management frameworks. By drawing from multiple disciplines, DEM can address the diverse factors influencing disaster outcomes, fostering a more inclusive and comprehensive approach to disaster planning and response. Equally, legislative frameworks play a critical role in enabling such adaptability and collaboration. Effective policies must support decentralised decision-making and multi-stakeholder coordination, ensuring that DEM systems can respond dynamically to evolving disaster environments.

The main arguments of this paper illuminate the current landscape of DEM, highlighting persistent challenges such as the marginalisation of local actors, the siloed nature of interorganisational collaboration, and the failure to address socio-economic and cultural factors. These insights lay the foundation for integrating a CAS perspective, which provides a comprehensive lens to understand the dynamic, non-linear interactions that define disasters. However, the application of traditional CAS principles within DEM presents challenges, including the inherent unpredictability of complex systems and the difficulty of achieving unified responses in multi-agency, multi-sectoral environments. These limitations necessitate a tailored approach that balances the strengths of CAS with the unique demands of the DEM context.

The proposed CADEM Framework builds upon the foundational elements of CAS while addressing its challenges through a holistic and adaptive perspective. This framework emphasises decentralised decision-making, interorganisational collaboration, and emergent behaviours as key components of an effective disaster management system. Unlike traditional CAS principles, which can be difficult to operationalise due to their complexity, CADEM reframes unpredictability as an opportunity for innovation, encouraging inclusive strategies that leverage the strengths of human factors and organisational diversity. By positioning DEM as an interconnected continuum rather than a series of distinct phases, the framework fosters a cohesive, adaptive system capable of responding to the evolving demands of complex disaster environments.

This transition towards a CAS-oriented model represents an exciting opportunity to recognise the diverse participants within the DEM system and the unique attributes they bring to the table. By embracing the principles of flexibility, collaboration, and inclusivity, the CADEM Framework provides a pathway for holistic solutions throughout the disaster lifecycle, enhancing resilience and adaptability in today's complex societal landscape. The need for an evolving DEM framework that integrates CAS principles is evident. The proposed CADEM Framework addresses critical gaps within existing models, offering a robust approach to managing the multifaceted challenges of contemporary disasters. Future research should focus on exploring practical applications of this framework, such as pilot programs, cross-agency collaboration initiatives, and policy reform. Additionally, integrating CAS elements into DEM systems requires continued attention to methodological challenges, particularly in balancing centralised coordination with decentralised adaptability. By fostering a more responsive, inclusive, and resilient DEM system, the CADEM Framework positions DEM to effectively navigate the unpredictable and interconnected nature of contemporary disasters.

CRediT authorship contribution statement

Todd Miller: Writing – original draft. **Loic Le Dé:** Writing – review & editing, Supervision. **Katherine Hore:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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