Critical Infrastructure Resilience: Findings from a Systematic Review

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Globally, critical infrastructure (CI), such as energy, water, transport, information and communication technology, health, food supply, banking and finance, government services, safety and emergency services are required to ensure the provision of public services, economic growth and social development. Since the late 1990s, countries have been designing and implementing public policies and strategies to protect CI from various threats. Initially, policies were focused on the physical protection of CI to physical hazards such as terrorism due to events such as the 9/11 terrorist attacks in the United States and 2004 Madrid and 2005 London terrorist attacks but have quickly evolved to reflect the evolving and unpredictable global landscape of threats such as natural disasters, ageing infrastructure, cyber-attacks and many more.

Scholars have noted that the adoption of “critical infrastructure resilience” is necessary to ensure the safety and well-being of global communities in light of the evolving landscape of threats, including political threats and the intricate interconnectedness of global infrastructure. Research of CI resilience shows promising signs of interest among scholars. However, some of the most fundamental questions around the concept are still not widely understood, such as: How is critical infrastructure resilience defined? How is it assessed?; How can governments, policy leaders, practitioners and CI owners and operators enhance CI resilience? For these reasons, this study seeks to fill the research gap and establish the current knowledge on critical infrastructure resilience among the literature and address several fundamental questions to ensure a consistent understanding of the concept. This study aims to contribute to knowledge about critical infrastructure resilience by systematically reviewing relevant scholarly literature, analyzing its major and minor themes, and identifying future research directions.

The results draw several conclusions including the limited research of CI resilience outside of engineering, a lack of consensus surrounding the definition of CI resilience and a narrow perspective of the risks to CI. Finally, future research recommendations include an increased research focus on societal resilience and additional examination of non-physical risks. Furthermore, an analysis of CI resilience among a more diversified set of industries including healthcare, emergency services, food production and distribution and essential manufacturing and an assessment of non-technical solutions to enhance CI resilience.

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Dedication

This thesis is dedicated to my late grandfather, Luka Biskupovic, who dreamed of attending university in the Former Yugoslavia to study political science but was never able to. Your curiousity and passion for learning lives on through me and all of my achievements in academia are in honour of your memory.

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Chapter 1: Introduction

1.1 Problem Statement

Communities rely on critical infrastructure (CI) to ensure the provision of critical public services, economic growth and social development. Globally, the dominant sectors are energy, water, transport, information and communication technology, health, food supply, banking and finance, government services, safety and emergency services. Major and minor events can have significant impacts on critical infrastructure, which can cause extreme harm to the well-being of society. Some recent examples include the 2021 ice storm in Texas, which overwhelmed the state's electricity infrastructure, caused power outages to nearly 4.5 million homes for several days and resulted in 57 deaths. Furthermore, the electricity outage cascaded into failures for every power source, including natural gas, coal, wind and nuclear (Sparber, 2021). More recently, Hurricane Elsa in the United States resulted in heavy rains and flash flooding in major subway stations and roads in New York City in July 2021 (Adelson & et al., 2021). Cyber-attacks such as the one that occurred in February 2021, where a hacker attempted to raise the sodium hydroxide levels in a Florida cities' water supply to poison residents, are a growing threat to society as CI becomes increasingly dependent on interconnected networks (Greenberg, 2021).

Since the late 1990s, countries have been designing and implementing public policies and strategies to protect CI from various threats. Initially, policies were focused on the physical protection of CI to physical hazards such as terrorism due to events such as the 9/11 terrorist attacks in the United States and 2004 Madrid and 2005 London terrorist attacks but have quickly evolved to reflect the evolving and unpredictable global landscape of threats such as natural disasters, ageing infrastructure, cyber-attacks and many more. Notably, CI policies and strategies have now considered climate change a significant threat to social and economic well-being. The increasing frequency and intensity of extreme weather and natural disasters have shown the potential to impact CI's functioning severely. Furthermore, global widespread market liberalization and privatization policies, particularly in North America and Europe, have led to the transfer of ownership and operation of CI from the government to the private sector. Alongside this transition, there has also been a trend of deregulation of several industries and fiscal austerity, leaving many CI sectors self-regulated and underfunded (Curt & Tacnet, 2018; Murray & Grubesic, 2012; Pursiainen, 2018). Furthermore, globalization has resulted in an unprecedented level of interconnectedness between countries' CI leaving no country immune to the impacts of failure or disruption to their neighbouring countries' infrastructure (OECD, 2019; Pursiainen, 2018). For example, a power outage in 2003 in Ohio resulted in several power failures in southeastern Canada and affected other sectors such as financial, transportation, and manufacturing (OECD, 2019).

Scholars have noted that the adoption of "critical infrastructure resilience" is necessary to ensure the safety and well-being of global communities in light of the evolving landscape of threats, including political threats and the intricate interconnectedness of global infrastructure. Several governments have addressed the need to adopt critical infrastructure resilience policies and strategies, but the state of academic knowledge around the concept has not been well-established. The idea has emerged in scholarly literature relatively recently. It shows promising signs of interest by researchers, but some of the most fundamental questions around the idea are still not widely understood, such as: How is critical infrastructure resilience defined? How is it assessed?; How can governments, policy leaders, practitioners and CI owners and operators enhance CI resilience?

For these reasons, this study seeks to fill the research gap regarding the current state of knowledge of critical infrastructure resilience among the literature and address several fundamental questions to ensure a consistent understanding of the concept. This research will be conducted through the use of a systematic review which is a methodology that seeks to locate and synthesize the best available evidence related to specific research questions. Systematic reviews also seek to advance a research field to better inform decision-making for policy and strategy design. Fewer than than one percent of systematic reviews exist outside the health sciences field but are growing in popularity in social sciences due to their ability to examine complex problems to provide credible, evidence-based solutions for policymaking (Mallett et al., 2012; Petticrew, 2001).

1.2 Research Objective & Questions

This study aims to contribute to knowledge about critical infrastructure resilience by systematically reviewing relevant scholarly literature, analyzing its major and minor themes, and identifying future research directions. Given the substantial research conducted on the topic of critical infrastructure and reislience there is an opportunity to establish common themes and research gaps among the existing knowledge. The initial research objective seeks to explore critical infrastructure resilience more broadly to synthesize understanding of the case. As such, the following research questions were developed to guide the study:

1. How is CI resilience conceptualized in the scholarly literature?;
2. What is the current state of knowledge and extant research findings of CI resilience?
3. What are the necessary future research directions to further advance knowledge of CI resilience?

1.3 Thesis Organization

This thesis comprises of six chapters. Chapter two (Literature Review) is divided into three parts. The first part provides an introduction to the literature surrounding critical infrastructure and the evolution of critical infrastructure protection in policy and scholarly literature. The emphasis on critical infrastructure protection has limited the understanding of how to reduce the overall societal impacts from CI disruptions which has called for an evolution from the concept.

The second part provides the academic origins and development of resilience and an introduction into the concept of critical infrastructure resilience. Although the concept of resilience emerged in different disciplines, it has been adopted by many research disciplines and adapted to understand and address growing issues specific to certain research fields. Critical infrastructure resilience was introduced in the last decade as the perspectives and approaches to managing risks to CI have evolved. The concept of CI resilience is relatively new and many fundamental questions remain unanswered. The research surrounding the concept is growing and there is little consensus on several aspects of the term, such as how it is defined, how it is assessed and how it can be enhanced in practice.

The third part provides an introduction into systematic reviews, their evolution from health sciences literature to other fields and the research gaps in systematic reviews of CI resilience. Systematic reviews vary from typical literature reviews as they are designed to locate and synthesize the best available evidence related to a specific research question through a specific process to ensure transparency and reproducability of the research study. Although systematic reviews are less common outside of the field of health sciences, they are growing in popiularity due to their ability to systematically review a topic area, synthesize a large amount of information to establish a comprehensive understanding of a concept and assist in decision-making for policymakers and practioniers by providing them with detailed, evidence-based research.

Chapter three (Methodology) describes the systematic review process in detail, which investigates the research questions. The methodology chosen for the objective of this research was a systematic review as they are regarded as the most effective means to synthesize information from multiple research sources with similar research questions. They follow a standard methodology to ensure they are reproducible and they examine a collection of documents selected based on clearly defined and defensible criteria. The researcher used the guidance and steps pioneered by Boland et al., (2017). In addition, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was also utilized and adapted for a qualitative systematic review due to its popularity and each step of the methodology follows this guidance to ensure a high degree of transparency and quality reporting. Descriptive and thematic analyses were executed for the planned methods of synthesis and analysis. A descriptive analysis provides a thorough descriptive account of the field of study for the reader to understand the research. The thematic analysis draws insights from patterns in the data to identify key themes and was guided by the six-phases of thematic analysis pioneered by Braun & Clarke (2006).

Chapter four (Results) synthesizes the research findings in two parts: a descriptive and thematic analysis. The descriptive analysis provided results which included a table of methodological characteristics, including research pecularities, objectives and keywords. Furthermore the descriptive analysis results found that the publication dates of the data range from 2006 to 2020 with most of the dataset's publication dates in the last three years. The study locations of the dataset are almost exclusively in the Global North, with most of the data coming from the United States. The journal types are focused in the engineering field with some indication of interdisciplinary analysis of the concept in other research fields such as human geography, disaster management and political sciences. The methodology of the data is split almost evenly between qualitative and quantitative data with a much smaller proportion of research utilizing mixed methods.

Chapter four (Results) also presents several results from the thematic analysis, The first part goes over the following themes: defining CI resilience, types of CI, risks to CI and types of CI resilience. The results indicate that the definition of resilience remains more closely linked to the original definition from the engineering and physics field and emphasizes the protection of and minimization of impacts on physical structures. The research places an over-emphasis on technical resilience despite the indication that there should be a shift towards societal resilience. The research focuses primarily on physical risks to CI and there is limited analysis of non-physical risks to CI such as cyber-attacks and political threats. The primary infrastructures analyzed in data are energy, transport and water and there is less research conducted analyzing the resilience of other vital CI sectors such as healthcare, emergency services and food production and distribution.

The second part of the thematic analysis discusses the following themes: enhancing CI resilience, assessing CI resilience, case studies, frameworks and research gaps. The primary focus across the literature for enhancing CI resilience is technical solutions and there is indication of a hesitancy to discuss and analyze non-technical solutions such as regulation and other public policy tools. Although the research indicates some consensus surrounding the best indicators for assessing resilience based on some redundancy in the results, there is no confirmed consensus among the academic literature or real-life CI operation. The case studies in the literature focus entirely on the Global North and around the assessment of risk or enhancement of CI resilience based on physical hazards, focusing on the power, transport and water infrastructure sectors. The frameworks in the data are primarily quantitative, focusing on technical solutions to CI resilience, and there was limited discussion around how the frameworks would be applied in real-life and how actors (i.e. CI owners or operators, policymakers or practioners) could mobilize the frameworks. There were several research gaps presented in the literature, primarily that CI resilience remains studied predominately in technical fields which limits the knowledge and tools that can be utilized and adapted from other fields to assist in problem-solving. Finally, there is limited standardization of CI resilience assessment and the application of CI resilience frameworks has not been adequately explored.

Chapter five (Discussion) discusses the findings with the research questions and draws connections to Chapter two. Firstly, there is a lack of overlap with other research fields since CI resilience is focused in technical fields such as engineering, particularly fields which have substantial knowledge which could benefit the development of the concept such as ecology, natural hazards and disaster management. The definition of CI resilience requires four components: planning and preparation, reduction of impacts, minimal recovery times, and learning and evolution and should focus more so on ensuring the provision of vital services and less on the physical structures themselves. There is a narrow perspective to risk which focuses solely on physical hazards and does not reflect the growing landscape of threats which include several non-physical risks. Furthermore, the risk of climate change and its related threats such as flooding and extreme weather, are an ever-present threat which will continue to pose a risk to communities and there is further need to understand how natural hazards impact CI resilience. There is an over-emphasis on technical solutions to CI resilience and extremely limited research exploring and analyzing non-technical solutions such as various public policy tools. The research establishes the responsibility for CI resilience on the private sector, as most CI sectors globally are now privately owned and managed, and for this reason do not necessarily explore the responsibility of other stakeholders such as the public sector, the academic community, and consumers. Finally, there is no industry or academic consensus on the best methods for assessing the resilience of CI.

Finally, Chapter six (Conclusion) summarizes the research objectives, questions, methodology and findings and concludes with future research directions. Future research directions include the need to conduct more geographically diverse CI resilience research as the current research focuses almost entirely on the Global North, and specifically the United States. Future research should focus more on societal resilience by analyzing how social capital and networks can reduce the social and economic losses from disruptions to CI. There should be analysis conducted to understand the degree to which CI is at risk due to climate change and what measures, tools and technologies must be in place to ensure the resilience of CI. Non-physical hazards, such as cyber-attacks and political threats, should be the focus of future Ci resilience research to capture the wide range of risks posed to CI in modern society. CI sectors such as healthcare, emergency services, food production and distribution and essential manufacturing should be studied to understand their current degree of resilience in various regions and communities globally. Future research should examine and analyze the public policy tools in place aimed at enhancing CI resilience to provide a better understanding of non-technical solutions and their efficacy. Finally, additional systematic reviews of CI resilience should be conducted to further academically develop the concept and potentially address the limitations of this review.

Chapter 2: Literature Review

Part 1: Critical Infrastructure and Resilience

This literature review chapter is divided into three parts. The first part provides an overview of the current state of knowledge of critical infrastructure and a history of CI management in the North American context. The second part outlines the evolution of the concept of resilience and the connection to other fields. The third part describes the current state of knowledge of systematic reviews outside the fields of health sciences, particulary focusing on CI and resilience and outlines research gaps in the topics of CI resilience which would benefit as a result of a formal systematic review process.

1. Critical Infrastructure

Critical infrastructure in modern society can be understood as “buildings, facilities, systems or networks essential for maintaining the vital functions of a society, and the health, safety, security and economic and social well-being of the community, whose cessation or destruction would have a significant impact” (Curt & Tacnet, 2018, p.2441). Critical infrastructure is also the “central nervous system of the economy in all countries” and will not only allow for the functioning of a society but can contribute to an enhanced economy and social development (Yusta et al., 2011, p.6100). The dominant sectors are energy, water, transport, information and communication technology, health, food supply, banking and finance, government services, safety and emergency services. Canada and the United States supply a much longer list of CI sectors provided in Table 1 and 2, respectively.

Scholarly analysis and review of critical infrastructure is relatively recent and the dominant literature on this topic is concentrated within policy documents and legislation. The concept of “critical infrastructure” emerged in the early to mid-90s due to the growing threat of terrorism to North America and the scholarly literature slowly followed in the early 2000s. For example, the executive order that defined critical infrastructure in the United States was established in 1996 and listed eight infrastructure sectors considered “vital” to national security. Similarly, in 2001 the Government of Canada published the National Framework on Critical Infrastructure Protection and Effective Management. In 2009, the National Strategy for Critical Infrastructure was established and defined CI as “those physical and information technology facilities, networks, services and assets, which if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of Canadians or the effective functioning of governments in Canada” (Government of Canada, 2003, p.7). This report identified

Canada's established ten CI sectors including transportation; manufacturing; safety; water; food; government; energy & utilities; communication and information technology; finance; and healthcare.

Table 1: Canada Critical Infrastructure Sectors (Quigley, 2013)

Canada Critical Infrastructure Sectors (Federal, Provincial and Territorial)
Transportation
Manufacturing
Safety
Water
Food
Government
Energy and Utilities
Communications and IT
Finance
Health Care

Table 2: United States CI sectors (U.S. Department of Homeland Security, 2020)

United States Critical Infrastructure Sectors
Chemical
Commercial Facilities
Communications
Critical Manufacturing
Dams
Defense Industrial Base
Emergency Services
Energy
Financial Services
Food and Agriculture
Government Facilities
Healthcare and Public Health
Information Technology
Nuclear Reactors, Materials and Waste
Transportation Systems
Water and Wastewater Systems

Evolution of Threats to Global Critical Infrastructure

Initial discussion surrounding threats to CI was focused predominately on physical threats such as war and terrorism. As policy and scholarly literature around critical infrastructure has evolved, so has the understanding of the risks that pose a threat to CI functioning. Additional physical threats to global CI include extreme weather events, natural disasters, pandemics, and other disruptive forces that can cause its collapse or degradation. In 2012, Hurricane Sandy flooded roads and tunnels, which disrupted New York's subway lines, leaving many without transportation, and resulted in electricity shortages for 8.5 million households (OECD, 2019). More recently, the global pandemic of COVID-19 has had unprecedented impacts on global health systems, resulting in the overwhelming increase of hospitalizations in intensive-care units (Phua et al., 2020). In addition, non-physical threats such as cyber-attacks and political threats, such as the privatization of CI industries, deregulation, and fiscal austerity, have been identified as relevant emerging dangers within the literature.

Physical Risks

The early political debates surrounding the protection of CI centred on war and terrorism-related threats. The 1997 United States presidential report, for instance, stated that "while poor design, accidents, and natural disasters may threaten our infrastructures, we focused primarily on hostile attempts to damage, misuse, or otherwise subvert them" (Staff et al., 1997, p.14). The emphasis on war and terrorism was further reinforced in North American policy discussions and development following the terrorist attacks of 9/11, despite scholarly discourse that identified a wider range of threats to CI. Similarly, European policy development around CI protection occurred only after several terrorist attacks in European countries.

Canada's CI policies stem from an earlier period during the second world war (Boyle & Speed, 2018). At that time, governments recognized the importance of vital systems such as transportation, water, and energy, as well as their interconnections, and their potential to disrupt society if impacted. This recognition rose to a national security concern during the second world war as the United States and Canada became increasingly concerned about aerial bombardment and nuclear strikes. Canada's approach during this time was a centralized, government-led protection strategy established through the War Measures Act in 1914. The War Measures Act empowered the federal government to "exercise sweeping emergency powers upon declaration of 'war, invasion, or insurrection, real or apprehended'" (Boyle & Speed, 2018, p.219). Scholarly literature on this topic has focused on investigating the probability and potential impact of terrorist attacks on various CIs, particularly transportation infrastructures such as airports and subway systems, which are deemed attractive targets for attacks (Farahani et al., 2019).

From 2016-2021, the incidence of natural disasters has increased by two percent annually (Osei-Kyei et al., 2021). The increased occurrence and intensity of natural disasters have been identified as a significant threat to CI in the literature. Flooding and its threats to CI is a significant focus area of natural hazards research as it is the most common and wide-reaching natural hazard globally and the third most damaging natural hazard after storms and earthquakes (Wilby & Keenan, 2012). Flooding has resulted in costly and deadly impacts due to the increasing concentration of population and wealth in urban areas (Rehman et al., 2019). Climate change is altering many of the Earth's cycles, changing the frequency and intensity of natural hazards, mainly flooding, wildfires and droughts, and these factors are driving more natural disasters globally (Van Aalst, 2006). Understanding how flooding impacts on CI has emerged as an essential topic in scholarly literature, focusing predominately on the observations of specific, localized infrastructure impacts. For example, Deshmukh et al. (2011) concluded that the severity of impacts from the 2009 US Midwest floods resulted from weak infrastructure and damage to bridges, roads, power plants, water, and wastewater plants. Gordon & Little (2009) asserted that the actions following Hurricane Katrina in the form of government-led disaster relief funds perpetuated a cycle of inadequate preparation for CI disruption to flooding events. Miller et al. (2018) reported that the hurricane season in 2017 was the most devasting in history, resulting in $290 billion in damages to CI in the United States.

As extreme flooding events become more frequent and intense, the scholarship cannot capture the breadth of damage occurring to CI globally. There are countless examples of flooding events, their impacts on CI and the subsequent socioeconomic effects on impacted communities. Hurricane Katrina has been a popular focus of research into the intersection of flooding and CI. It was an extreme example of the severity of the impacts of flood exposure to weak CI. As extreme hurricanes have been increasing over the past decade, the research area is becoming more prominent among scholars. In particular, the case study of Hurricane Maria in Puerto Rico has now emerged as a scholarly focus. Puerto Rico suffered greatly as a result of Hurricane Maria due to weak and poorly managed CI. Most deaths resulted from the lack of power in health care systems, weak health care networks that could not ensure medication delivery, and contaminated wastewater (Klein, 2019). Two months after the hurricane, less than half of the 3.4 million residents had regained their electric power (Miller et al., 2018). Additionally, Hurricane Harvey in Texas resulted in several oil spills and the release of chemical contamination in the surrounding environment (Osei-Kyei et al., 2021). Murdock et al. (2018) outlined the growth of global flood damage, which is expected to total around the US $52 billion by 2050, much of which involves damage to CI such as power outages, traffic delays and flooded trains.

Another significant physical threat to CI discussed in the literature is the ageing of infrastructure, as much of the current infrastructure is old or has antiquated components that significantly increase vulnerability. Much of the CI equipment globally was constructed following World War II and has not been upgraded or updated. Furthermore, erosion due to the progression of climate change and the increased demand for CI services in urban areas are additional factors contributing to the ageing of infrastructure. Scholars have noted that these factors have accelerated the erosion and ageing of CI (Osei-Kyei et al., 2021). Due to ageing infrastructure, there is a risk of amplified impacts from external threats due to the unreliability and vulnerability of weakened CI systems.

Non-physical Risks

In addition to tangible, physical risks to CI globally, several relevant non-physical risks pose a significant threat to adequate protection of global CI. The non-physical threats include cyber-attacks and political threats such as growing fiscal austerity and de-regulation of CI industries.

As technology has advanced in the last few decades, CIs such as smart grids, air traffic, transportation, electricity and nuclear power plants have become increasingly dependent on digital control systems and networking resources (Osei-Kyei et al., 2021). Due to the increasing dependence on technology, CI is no longer isolated and is typically connected in a “system-of-systems” environment, relying on public networks, such as the internet, to ensure functionality and productivity. As a result of the technological interconnection between CI globally, they have become attractive targets for cyber-attacks, and scholars have noted the increased frequency of cyber-attacks (Genge et al., 2015). The exploitation of the technology that CIs rely on can lead to severe and dangerous impacts. Due to the complexity of the network systems, cyber-attacks remain a major challenge to prevent and they are therefore a significant threat to CI (Han et al., 2019).

Furthermore, CI systems have become more complex and interconnected and, due to widespread privatization and deregulation of essential public services, have become more institutionally fragmented in many sectors (de Bruijne & van Eeten, 2007). In Canada, for example, this includes the partial privatization of Hydro One--the primary electricity services provider--the privatization of Highway 407, and the emergence of “privatization creep” into many healthcare services (Levac & Wooldridge, 1997). As economic activities have become increasingly globalized, networks have become more interdependent, while institutions that manage CI sectors have become more fragmented, resulting in increased vulnerability (Michel-Kerjan, 2003). A power outage that occurred in northern Ohio in 2003, for instance, triggered cascading power failures in southeastern Canada and eight states in the United States, which affected other CI sectors, including energy, communications, financial, healthcare, food, water, transportation, safety, government, and manufacturing. An underlying factor that led to a widespread failure included inadequate communication channels between connected CI sectors resulting from fragmented authority (OECD, 2019).

Increasing austerity in nations has starved publicly owned institutions of resources to effectively manage risk and ensure the protection of CI (Curt & Tacnet, 2018). Approximately 85 percent of CI in the

United States is privately owned and controlled (Murray & Grubesic, 2012). Significant challenges for CI protection globally include cyber-attacks as well as the political threats such as the privatization and subsequent institutional fragmentation of many CI sectors, the rollback of regulations and fiscal austerity, and these pressures make it difficult for private actors managing CI to understand the risks and undertake protection measures (de Bruijne & van Eeten, 2007; May & Koski, 2013).

Management of Critical Infrastructure

Critical Infrastructure Protection

The importance of CI protection has increased due to the global evolution of interconnected economies and free trade which has resulted in a world where shocks to infrastructure systems in one region can create cascading global impacts (OECD, 2019). Furthermore, a failure of an entire system in one country can create dangerous consequences across other CI systems within the same region. Policy discussions around critical infrastructure and its protection began in the 1990s in the United States. In 1996, former United States President Bill Clinton began a national study to understand the vulnerabilities of national CI and critical assets. The conclusions from the report found that CI was at serious risk due to the lack of warning systems to protect against imminent danger, poor communication-sharing between government and industries operating CI and limited government research and development budget for understanding CI risk (Michel-Kerjan, 2003; Robinson et al., 1998). Following the terrorist attacks on September 11, 2001, the United States established executive orders for CI protection (CIP) which led many other countries to undertake research surrounding risk to their own CI and how to protect it (Wiseman & McLaughlin, 2014).

In both Canada and the United States during the Second World War governments recognized the importance of “vital systems” such as transportation, water and energy, their interconnections, and their potential to disrupt society if impacted. Canada’s approach during this time was a centralized, government-led protection strategy established through the War Measures Act in 1914. The War Measures Act allowed the federal government to “exercise sweeping emergency powers upon declaration of ‘war, invasion, or insurrection, real or apprehended’” (Boyle & Speed, 2018, p.219). Canadian CIP evolved following the establishment of the Emergency Measures Organization (EMO) in the late 1950s, later renamed Emergency Preparedness Canada (EPC) in 1975, and the repeal of the War Measures Act in 1988. Following the repeal of the War Measures Act, the EMO began to rethink and broaden their understanding of vital systems and the potential threats that contributed to their vulnerability expanding beyond just war. The establishment of the *Emergencies Act* and *Emergency Preparedness Act* (EPA) in 1988 was the conceptual shift from physically protecting locations or assets to restoring operations of organizations and governments following a disaster otherwise referred to as business resumption (McConnell, 1998). In 2001, the Government of Canada published a national framework on Critical Infrastructure Protection and Effective Management that was composed of five pillars:

1. Putting the Government of Canada's infrastructure and emergency management house in order
2. Enhancing and establishing sustainable federal and national partnerships
3. Enhancing the national operational capability
4. Implementing effective, targeted programs
5. Strengthening the policy framework (Eggleton, 2002)

Critical Infrastructure Stakeholders

During this time, the scholarly literature outlined four relevant stakeholder groups in the field of CI protection: 1) the government, which is responsible for ensuring security, public safety, economic wellbeing and the continuation of government services; 2) the private sector, which is mainly responsible for the operation of CI sectors; 3) the academic community, which researches different fields around CI protection and; 4) the consumers of the CI services, which expect the continual operation of their vital services without interruption (Abele-Wigert, 2006). There is significant scholarly debate surrounding the responsibility for CI protection. Widespread neoliberal and free-market ideologies encourage de-regulation by government entities, as proponents assert regulation hinders the success of privately owned and controlled goods and services. Furthermore, proponents of the same ideologies note that market forces and voluntary action are sufficient at ensuring an adequate supply of goods and services to meet the required demand (Lewis, 2005).

As many CI sectors globally transitioned to become privately-owned and controlled, scholars noted that the free-market ideologies come directly into conflict with CI protection. Firstly, even if a CI sector is privately owned and operated, it still provides a vital service required to ensure the operation, security and well-being of society and the economy. Proponents argue that vital services should be considered public goods and therefore are candidates for market failure, which indicates that market forces can not effectively manage their provision (Lewis, 2005). Second, in the absence of government intervention ensuring CI protection, private actors do not receive benefits for public safety and well-being. They can externalize threats, indicating that relying on private actors alone is not enough to ensure adequate CI protection (de Bruijne & van Eeten, 2007).

However, scholars also note that there are many limitations to expecting governments to take on sole responsibility of managing CI during crises. In the event of disasters and crises, the public expectation is that governments will respond to ensure the protection of CI, but there are many barriers to government's working alone, such as fiscal constraints and necessary collaboration with private sector CI. Governments initially established all policy and regulation which seeks to ensure CI protection but increasingly privatized CI sectors, market liberalization, and limited involvement by governments into the private sector in countries such as the United States has led to significant ambiguity around which stakeholder has the authority over CI. Even in Canada and the EU, there is some ambiguity around the responsibility for CI and the indication that there is a sizeable voluntary responsibility for the private sector to act. Although there is a public perception that the government is solely responsible for the provision of vital services, scholars indicate that they likely lack the authority, resources, and knowledge to effectively do so during a crisis or disaster. In research and in practice, there is a lack of explicit coordination between the four stakeholders identified and each group's specific roles and responsibilities for CI protection (Pursiainen, 2018).

Defining "Criticality"

A significant limitation and criticism to understanding and mobilizing CI protection in the initial literature was the lack of understanding around the definition of "criticality." Scholars identified that the conceptualization of "critical" infrastructure or assets was varied and regionally specific. In the absence of a defined concept, it is challenging to analyze policies and practices for their efficacy and presented a significant obstacle to academic, as well as practical, dialogue (Dunn, 2005; Metzeger, 2004). The lack of consensus around what is critical has little academic discussion since different groups cannot agree on what the problem is and what precisely CI sectors need to be protected (Metzeger, 2004). Furthermore, defining a particular number of sectors as "critical" glossed over the reality that CI sectors are in actuality interconnected, which results in significant interdependencies across sectors that must be understood (Dunn, 2005). Furthermore, scholars criticized the lack of understanding of CI and criticality overall as a socio-political issue since the degree to which damage to society due to disruption or disaster to CI was acceptable is a political question and not a technical question (Dunn, 2005).

Metzeger (2004) presented two different understandings of criticality. The first is criticality as a symbolic concept related to its role or function in society. An example is a national landmark, such as the White House, which is necessary to ensure government services and security policy objectives . The second is criticality as a systemic concept related to its function in the broader system of infrastructures such as the importance of electric power to ensure the operation of other critical services. Furthermore, the author posits that the systemic understanding of criticality is more relevant to every day life since the symbolic understanding criticality is more closely related to the identity of a nation or national pride and less relevant to the security and well-being of society (Metzeger, 2004).

Critical Infrastructure Protection Policies

Early policy and scholarly literature surrounding CI focused primarily on protecting physical assets defined as critical, including protecting the physical structures, crisis prevention, and contingency planning (Pursiainen, 2009). The goal of CI protection is to "understand and prevent cascading failures that can trigger major nationwide disruptions of entire infrastructures and industries" (Ghosh, 2011, p.174). The emergence of the term CI protection originated in engineering and information technology which sought to understand how to protect closed systems from damages resulting from disruptions (Metzeger, 2004). Real-life examples that emerged from original CI protection literature to prevent crises from occuring include measures such as the Dutch flood protection systems and the segregation of birds infected with avian flu (Boin & McConnell, 2007). Contingency planning involved the "specification of roles and responsibilities; the allocation of materials, equipment and information systems, and the testing of systems under trial conditions" (Boin & McConnell, 2007, p. 53).

Scholarly literature indicates a characteristic that exists commonly between initiatives associated with CI protection is that they rely strongly on anticipation for managing risk. To effectively anticipate a threat to CIs, it is imperative to understand the properties and the probability of such a threat occurring and the scope of effective responses to prevent harm from occurring. Scholars criticize allocating efforts and resources towards an anticipatory approach to preventing harm to CI as it takes away resources that could be put towards strategies which are more capable of handling unanticipated threats (de Bruijne & van Eeten, 2007). Planning for crises can be counterintuitive as it is challenging to plan for unforeseen events and disasters effectively. Notably, Clarke (1999) proposes that planning for crises can overlook and disregard many unique challenges that emerge from disaster events. Planning for crises is essential but is considered not sufficient for adequate CI protection.

As significant policy around CI emerged globally and focused primarily on protection, scholarly literature, particularly in social sciences, presented widespread criticism of the concept due to its technical emphasis. A fundamental problem identified across the literature is that CI protection was academically developed and understood in highly technical and scientific contexts but then introduced into political agendas without developing the concept in a socio-political context (Metzeger, 2004). Exclusively understanding the quantitative crisis thresholds for CI is not enough to adopt adequate risk reduction strategies or protection policies, because "understanding and reducing vulnerability does not demand accurate predictions of the incidence of extreme events" (Metzeger, 2004, p. 204). The lack of perspectives of CI at the early stages of its political conceptions from socio-political and behavioural science contexts limited the understanding of the problems surrounding CI, barriers and challenges and the holistic solutions for effective risk management.

Furthermore, the usage of the term protection implies an "all or nothing" mentality where the infrastructure is either protected or not protected from threats which is not suitable for modern infrastructure vulnerabilities. Therefore scholars recommend the use of terms from natural sciences such as resilience, robustness, and adaptive capacities as they are more appropriate to address the complexity of CI (Metzeger, 2004). Historically, technical disciplines such as engineering and information technology have dominated the literature surrounding CI and CI protection. The focus on the technical aspects of CI protection has limited understanding of the topic (Abele-Wigert, 2006). Early literature on CI protection has almost entirely neglected the socio-political dimensions and was not integrated into many different disciplines, limiting the overall understanding of the complexity of the challenges which posed a threat to adequate protection of CI (Abele-Wigert, 2006).

Overall, the emergence of CI protection in technical and engineering contexts limited the understanding of how to reduce societal impacts from CI disruptions by emphasizing the anticipation and prevention of disruptions. The focus on the protection of CI has omitted the necessity for effective, proactive planning and resilience of CI. As CI protection strategies have evolved, scholarship indicates that resilience principles must be emphasized alongside physical asset protection, crisis prevention, contingency planning and post-crisis management to ensure effective CI protection.

2. Resilience

The word “resilience” originates from the Latin word *resilio* which means to jump back. The term was first established as a scientific concept in material physics in the 19th century. It was understood as a material’s ability to absorb energy when stressed and return to its original form after the stress was released (Bergström et al., 2015). It was then developed as an ecological concept and adapted to social systems with further developments applying the concept more broadly to the complex and interconnected socio-ecological systems (Zhou et al., 2010). The term “resilience” was popularised in in the ecological field through the foundational work of Holling, (1973) who explored how different behaviours in ecological systems can result in different approaches to managing resources. Resilience initially was understood as a system’s ability to absorb disturbances and then return to its equilibrium (Bhamra, 2011). Holling introduced the concept of resilience in his paper which explored the relationship between resilience and stability and described change models in the structure and function of ecosystems. Holling’s definition is now known as ecological resilience which is how much a system could be perturbed without shifting into a novel regime (Walker et al., 2006).

The term was further developed, extended to other research disciplines, and formalized as either “ecological resilience” or “engineering resilience”. In each discipline, many definitions of resilience have been used and proposed. Specifically in ecology, the term has been used in two contexts. One is the ability and time needed for an ecosystem to return to pre-disturbance conditions. The other is the original definition, which measures the systems' ability to absorb disturbances while maintaining the exact relationships between populations in the system. Ecological resilience can be composed of four attributes: scale, adaptive capacity, thresholds, and alternative regimes (Baho et al., 2017). Although some ecologists believe that resilience measures how soon a system returns to a previous state after a disaster, this understanding of resilience is now understood as engineering resilience. Academically, the measurement of engineering resilience has been thoroughly developed and well understood but the quantitative measurement of ecological resilience has been underdeveloped.

Resilience has been most prominent in sciences such as psychology and ecology. The psychology and health sciences fields adopted the concept as a subject’s ability to thrive despite adversity in the 1970s (Bergström et al., 2015, p.33). However, it has increasingly been employed in political science, business, sociology, history, disaster planning, urban planning and international development (Martin-Breen & Anderies, 2011).

The concept of resilience has also emerged in fields such as safety science. The definition was adapted from the origin in engineering to address safety concerns. Safety science literature emphasizes that resilience is the ability to maintain normal operations during disturbances and that a failure-free environment is possible through engineering resilience. Furthermore, engineering resilience scholars highlight that the most vital characteristics for a complex sociotechnical system are adaptive capacity and flexible response to unanticipated events (Bergström et al., 2015).

It has been adapted frequently in different disciplines and remains as a shared conceptualization of the term resilience (Zhou et al., 2010). The literature alludes to the lack of cohesion and unification between resilience definitions across different research disciplines. Despite the breadth of resilience definitions and frameworks, the literature indicates three established frameworks for the concept: engineering resilience, systems resilience, and resilience in complex adaptive systems (Martin-Breen & Anderies, 2011).

Engineering resilience is the ability to bounce back after some type of stress occurs. Engineering resilience can apply at the individual level, where a person can recover emotionally and psychologically after experiencing varying degrees of stress or applied technically. An engineered systems such as buildings, bridges and other infrastructure can endure stresses and return to its regular operative goals. A limitation identified with this type of resilience is that on certain occasions the objective is not to return to an equilibrium or previous state but rather to change and evolve. Systems or individuals that change after stresses can still classify as resilient (Martin-Breen & Anderies, 2011).

Systems resilience is maintaining system function(s) even when the system experiences stresses or disturbances. Although the definition of essential system functions can vary due to region or scale, there are several fixed functions required for human survival and well-being such as food, water, and medical care. For example, this type of resilience focuses on ensuring certain functions can be maintained such as government services following terrorist attack or electricity services during a winter storm. A limitation identified with this type of resilience is that even if certain essential functions cannot operate, some systems have the adaptive capacity to ensure survival. Through behaviours such as self-organizing in individuals or changes in ecosystem species can ensure a functioning system (Martin-Breen & Anderies, 2011).

Finally, resilience in complex adaptive systems is the ability to learn from disturbances and stresses to develop new ways for the system to operate to improve its ability to cope with future disturbances, which can mean that the system structure can change and the system can continue. A vital principle of this type of resilience is transformability which is the ability for the system to change and perform a new function (Martin-Breen & Anderies, 2011).

Resilience is also understood to be the function of the vulnerability and adaptive capacity of the system. The vulnerability of a system is a system's susceptibility to harm, or more broadly is a system's exposure to threats, external stresses and the degree to which the system is affected by the threats and its capacity to respond to threats. Furthermore, adaptive capacity is a system's ability to respond to a threat and evolve to accommodate the threats or changes, including establishing a new system equilibrium or stability domain. An additional component to the concept of adaptive capacity is learning from disruptions to better cope with future unknown threats. Fiksel (2004) proposes four characteristics that determine resilience: diversity, efficiency, adaptability, and cohesion described in further detail in Table 3.

Table 3: Four major system characteristics that contribute to resilience (Fiksel, 2004)

System Characteristic	Details
Diversity	The existence of multiple forms of behaviour
Efficiency	Performance with modest resource consumption
Adaptability	Flexibility to change in response to new pressures
Cohesion	Existence of unifying relationships and linkages between system variables and elements

The fields of climate change and natural hazards adapted the concept of resilience to help understand how to address several growing issues. Scholarly literature criticizes policy approaches that rely heavily on short-term and technological fixes as they fail to address the broader issue of system resilience. A challenge in improving resilience for complex problems like climate change is understanding how improving one stressor can impact the broader system. For example, a coastal town experiencing sea-level rise due to coastal erosion might take action to improve that individual problem by directing investments towards an action targeted at one problem. Instead, the town should consider allocating resources towards actions that improve overall resilience, improving their overall adaptive capacity. Climate change presents a unique challenge to resilience as it is nonlinear. There are progressive changes not expected by systems which emphasize the need for transformability for resilience. Utilizing responses based on past experiences can limit the perspective for resilience solutions and reduce future options. Furthermore, an analysis of system stressors and responses for the issue of climate change globally concluded that in the context of climate change, factors such as top-down governance structures, the limited connection between actors of different scales and problems framed as technical with short term horizons severely reduced the resilience of the impacted system (Adger et al., 2011).

Scholarly literature indicates that resilience is an essential characteristic for communities to reduce vulnerability to natural hazards. Furthermore, scholars note that the most traditional definition of resilience that is measured based on a system's ability to return to a previous state after a disaster is undesirable in the context of natural hazards. The previous state impacted by a natural disaster has proved itself as vulnerable and therefore it is not desirable to return to a previous state as it would remain vulnerable to future disasters. Resilience to natural hazards is more closely related to later definitions of resilience which focus on improving the functioning of systems and measures resilience based on the ability of the system to learn and adapt from disasters to increase their capacity to cope with future events. A significant criticism of resilience in scholarly literature is that there are many different definitions of the term across disciplines. The implication is that the concept is confusing and difficult to operationalize in practice. Rather than an observable and measurable definition, the term has become an umbrella concept for a multitude of system characteristics deemed desirable. Without an explicit and measurable definition, resilience remains a vague concept of interpretation instead of a practical policy or management tool (R. J. T. Klein et al., 2003).

Natural hazards are a concrete example of a threat that has frequently occurred in an unprecedented manners due to their occurrence and severity. Although specific preventative measures are taken, future disasters cannot be prevented from occurring in form, magnitude and location. Therefore, human systems must be able to recover effectively from disasters, which makes resilience an essential concept in natural hazards and disaster research. Vulnerability assumes the potential for loss in a system by accounting for the likelihood of exposures and susceptibility to damage. The varied definitions include Turner et al. (2003), who define vulnerability as the degree to which a system could experience harm as a result of a threat and Etkin et al. (2004), who define it as the likelihood that a system will suffer from a threat or hazard.

Disaster resilience is the ability to resist and recover from the loss caused by an extreme natural event with the shortest possible time with limited external assistance. Disaster resilience is assessed using pre- and post-disaster data and improves the abilities of the system to resist and recover from hazards. In contrast, vulnerability focuses more on the pre-disaster data to understand the exposure and sensitivity of the system and assists in preparation for future disasters. Disaster resilience includes two properties: inherent resilience and adaptive resilience. The former is determined by the structure and functions of the system during normal circumstances, and the latter is the system's ability to resist and recover from disasters and assesses the system's ability to learn from the disaster and evolve (Zhou et al., 2010).

Furthermore, disaster management literature emphasizes the concept of *societal resilience,* which is a shift towards a local and decentralized responsibility for safety and security within a community that includes all sectors of society: all levels of governments, businesses, the non-government sector and individuals (Bergström et al., 2015). For example, Sweden launched a campaign called "72 hours," which aims to ensure all households and businesses can remain self-sufficient for the first 72 hours after a crisis or disaster and similarly. "Get Ready Queensland" in Australia is a similar campaign which involves a network connecting households, business and government to enhance societal resilience during bush fire season (Bergström et al., 2015).

3. Critical Infrastructure Resilience

"Critical infrastructure resilience" has emerged in scholarly literature in the last decade or so, but many fundamental questions about the concept remain (Rød et al., 2020). Due to the emergence of CI literature in the engineering field, the classic approaches to crisis and risk management focused too much on a "scientific process" where it was necessary to know all relevant variables and develop optimized solutions. For this reason, scholars introduced the concept of CI resilience which seeks to go beyond traditional risk management approaches by taking into account unexpected events. In contrast, CI protection historically focused almost exclusively on anticipated events and preparing and preventing them (Labaka et al., 2016; Lindblom, 1959). The relevancy of managing the impact of natural disasters on CI has facilitated the transition into integrating resilience into CI literature as disaster research strongly indicates that societal resilience, which is the resilience of citizens, first responders, and operational commanders, is needed for effective response during disasters (Barton, 1969; Dynes, 1970; Drabek, 1986). Furthermore, as the lack of coordination of roles and responsibilities between the four stakeholders identified in CI protection, societal resilience has been identified as a goal for the assurance of the health, social and economic wellbeing of society. Societal resilience seeks to enhance the capacities of various actors (households, businesses, governments and non-government actors) to better cope with and recover from disasters through education and cooperation with the public and private sectors (Bergström et al., 2015).

The integration of resilience into CI academic literature has been discussed for the last decade. However, the integration between the two concepts remains limited, and a robust and fundamental understanding of "critical infrastructure resilience" is a significant research gap (Rød et al., 2020). Some scholars have proposed what CI resilience might look like, such as enhanced risk assessment tools, analytical frameworks that model CI resilience and private-public partnerships focused on regional approaches (Egli et al., 2019). Others have proposed that CI strategies to enhance societal resilience include preparing first responders, business continuity planning, the collaboration between communities and private owners of CIs, joint preparation, joint training, and training leaders (Boin & McConnell, 2007). Murray and Grubesic (2012) propose a "Critical Infrastructure and Key Resources Information Sharing Environment," which provides both tools and a secure system for allowing infrastructure providers to "share information, develop improved security protocols, evaluate risk, respond to events and enhance CIKR resilience" (p. 63).

Although there is some research on CI resilience, there is little consensus on how exactly it is defined, how it is assessed, and how it can be enhanced in practice. The historical literature on CI protection, which was more preventative and anticipatory, has provided substantial insights into protecting society from threats. However, there is an opportunity to understand how CI resilience is being framed and discussed in the literature to establish the connection between the two concepts to further advance knowledge around how societies globally can improve their resilience to physical and non-physical threats.

Part 2: Systematic Reviews

1. Systematic Review

A systematic review differs from a typical literature review. It is designed to locate and synthesize the best available evidence related to a specific research question, advance a research field, and make decisions about policy development and other interventions for change. Systematic reviews are considered the most effective means to synthesize information from multiple research sources with similar or identical research questions (Boland et al., 2017). Features that differentiate the systematic review from other forms of the literature review are its standardized methodology, which ensures it is reproducible, and the selection of documents and sources based on clearly defined and defensible criteria (Berrang-Ford et al., 2015; Boland et al., 2017). Steps required in a systematic review are the "definition of the question or problem, identification and critical appraisal of the available evidence, synthesis of the findings and the drawing of relevant conclusions" (Boland et al., 2017, p.2). Systematic reviews improve on traditional literature reviews because they assist in reducing implicit researcher bias since they adopt broad search strategies, predetermined search strings and uniform inclusion and exclusion criteria. They require that the research includes and reviews studies outside of their subject areas and networks. Traditional literature reviews also focus more on the results of studies without considering design, data, and methods, whereas systematic reviews incorporate analysis of the evidence, impact, validity, and causality of studies.

When executed effectively, systematic reviews have an obvious advantage over traditional literature reviews. They improve transparency, include a greater breadth of studies, require more objectivity and reduction of implicit bias and encourage researchers to think more critically with the quality of evidence (Mallett et al., 2012). Systematic reviews are considered a "rigorous method to map the evidence base in an as unbiased way as possible and to assess the quality of the evidence and synthesize it" (Mallett et al., 2012, p.446). Systematic reviews are usually peer-reviewed and have recently been associated with research networks such as the Cochrane Collaboration for medicine and the Campbell Collaboration for education, crime and justice and social welfare. The objective of these research networks is to minimize bias, reduce duplication of research, keep the reviews updated and provide a library of all the reviews in that field (Mallett et al., 2012).

2. Systematic Reviews outside of Medicine

Systematic reviews are typically utilized as formal, strictly standardized review papers in health sciences and fewer than one percent of systematic review documents in the Web of Science database focus on areas outside of health sciences (Boland et al., 2017). Systematic reviews were first applied in the medical sciences in the 1970s but have been growing in popularity in research fields outside of medicine (Mallett et al., 2012). Although social scientists have expressed the need to review literature without bias, the prevalence of systematic reviews in fields outside of medicine has only emerged in recent years (Petticrew, 2001). The increased interest in using systematic reviews outside of health research has been primarily due to the need to improve decision-making for policymakers and practitioners by providing them with detailed, evidence-based research to assist in the process (Mallett et al., 2012).

The limited use of systematic reviews outside of medicine is likely because they are contentious in the social science community for various reasons. One example of criticisms include the notion that systematic reviews prioritize a particular research methodology (e.g. randomized controlled trials), which is not prevalent in other research fields, such as social sciences. Other reasons include the inability for systematic reviews to synthesize crucial data which utilizes complex interventions and multiple outcomes. There is also currently no room for theory to play a role in the review, primarily since a theory of change guides social research. Scholars suggest multiple guiding principles for systematic reviews outside of the medical field such as developing methods for reviewing complex issues, interventions and outcomes. Furthermore, scholars suggest ensuring the review provides evidence that can be easily accessed and used by policymakers, practitioners, and public members. Hence, they use the best information to inform their decisions (Nagyova, 2015).

There is a common misconception that systematic reviews are the same as traditional reviews and that they simply review a large amount of content, but they are not just reviews of large quantities of literature, and the objective of the methodology is not to provide a “comprehensive review.” Their objective is to answer a specific question, reduce bias, appraise the quality of included studies, and summarize them objectively. An additional misconception is that systematic reviews are of no relevance to the “real world” since systematic reviews are focused primarily on disease outcomes in medicine and randomized controlled clinical trials conducted in closed, simple healthcare systems and do not consider the complex outside social world. However, systematic reviews have examined complex and contentious policy and social issues and provide credible, evidence-based solutions for policymaking (Petticrew, 2001). For example, systematic reviews analyzed whether spending more money in schools can improve educational outcomes, if job absenteeism is an indicator of job dissatisfaction and whether there is an association between poverty, income inequality and violence (Petticrew, 2001)

In the field of international development, for example, many donors are under pressure to spend money on practices that result in increased development and humanitarian outcomes. For these reasons, there has been an increased interest in "evidence-based policymaking," which uses empirical evidence in the design of policies and programmes in developing countries (Mallett et al., 2012). Due to the systematic review's rigorous and transparent literature review, many fields outside medicine have been increasingly using systematic reviews (Petticrew 2001).

Many systematic reviews address natural hazards and have been published in medical journals to quantify health impacts to justify and inform other strategy and policy actions. Since natural hazards typically result in many health impacts to a region, medical literature includes an extensive synthesis of physical and mental health impacts from flooding (Doocy et al., 2013). Additionally, reviews of tools to manage the health impacts of natural hazards have been conducted, such as understanding the role of occupational therapists in emergency response and analyzing gender disparity in the impacts of hazards with objectives of quantifying and reducing health impacts from natural hazards (Parente et al., 2017; Sohrabizadeh et al., 2014). Medical literature provides a solid basis for conducting and executing systematic reviews that are replicable, and the researcher will use them as a reference for the design of the methodology.

The topic of disaster risk reduction (DRR) is prevalent among systematic review literature in natural hazards due to the urgent need to understand and reduce natural disasters (Aghaei et al., 2018). Systematic reviews on DRR have focused on consolidation and analysis of topics such as effective DRR education strategies, understanding behaviour that might result in an increased risk of impacts as well as assessing governance and management of pre-disaster planning (Aghaei et al., 2018; Ahmed et al., 2018; Raikes et al., 2019). Another critical theme in systematic reviews for DRR is the tools to assess social impacts effectively and quantify economic impacts of disasters to guide efficient strategy formulation (Eckhardt et al., 2019; Sohrabizadeh et al., 2014). Additionally, Eckhardt et al. (2019) provided new insight into the importance of using grey literature in systematic reviews.

Disaster management, distinct from but related to DRR, is a topic area seemingly common among systematic reviews of natural hazards. The systematic reviews in this topic area have sought to define the term "disaster management," as there is no consensus around the definition in academic literature (Lettieri et al., 2009). Additional systematic reviews have sought to improve the modelling of natural hazards to better forecast and communicate future disasters (Anshuka et al., 2019). There has been a thorough analysis of DRR and disaster management topics among systematic review literature of natural hazards.

Three concepts assessed in systematic reviews of natural hazards include vulnerability, resilience and adaptation. Specifically, systematic reviews of natural hazards related to vulnerability pose questions about defining and assessing vulnerability to natural hazards, which is vital for implementing adaptation and improving resilience (Patel et al., 2017). Some systematic reviews have sought to further understand vulnerability by reviewing methods used to determine flood vulnerability and identify specific indicators to measure social vulnerability in disasters (Fatemi et al., 2017; Rehman et al., 2019).

There are only three systematic reviews that focus on flood risk management (FRM), two of which were published in 2019. Reducing the impacts from flooding historically followed a resistance-based approach, composed of principles such as protection, response and recovery (Morrison et al., 2019; van Popering-Verkerk & van Buuren, 2017). Flood management has evolved into a more holistic, resilience-based approach composed of principles such as flood prevention, defence, mitigation, preparation and response, and recovery (Henstra & Thistlethwaite, 2017; Morrison et al., 2019). Systematic reviews in this field have sought to define resilience as a concept in FRM literature to operationalize it better, understand the current status of flood risk perception and communication as sufficiently synthesize methodological information from community FRM strategies in the United States (Kellens et al., 2013; McClymont et al., 2020; Sadiq et al., 2019). Despite the need for improved FRM among communities and the understanding of effective operationalization of the concept, there is a limited synthesis of academic literature regarding this topic, particularly in Canada, where flooding is the most dangerous and costly natural hazard that is worsening due to climate change.

3. Research Gaps in Systematic Reviews of Critical Infrastructure Resilience

Despite its emergence in the literature, "critical infrastructure resilience" has yet to be explored using a comprehensive systematic review. A systematic analysis of critical infrastructure resilience must synthesize the breadth of information and guide evidence-based solutions. Some academic literature reviews exploring the concept have focused primarily on reviewing technical solutions for assessing or enhancing CI resilience (Curt & Tacnet, 2018; Mottahedi et al., 2021). In addition, one study reviewed the potential threats to building CI resilience (Osei-Kyei et al., 2021).

Since the concept has emerged in academic literature relatively recently, it will be beneficial to systematically review this topic area to synthesize the information available to establish a comprehensive understanding of the concept. There is a need to establish an understanding of the term in academic literature. More specifically, how is CI resilience conceptualized in the scholarly literature? (e.g. how is critical infrastructure resilience defined?; what infrastructure is considered critical?; what are the threats to CI resilience?); what is the current state of knowledge and extant research findings of CI resilience? And what are the necessary future research directions to further advance knowledge of CI resilience? As threats such as cyber-attacks, climate change, natural hazards and many more unanticipated risks pose a serious threat to the well-being of society, there is a need for an analysis of current strategies and policies and their ability to address the growing issue. Furthermore, there is a need to develop and implement strategic and evidence-based solutions to address imminent damaging social and economic impacts.

Chapter 3: Methodology

The purpose of this chapter is to describe the methodology chosen for this research study and provide a thorough explanation of the methods undertaken to answer the research questions. The chapter begins with an overview of the methods for the search strategy, data collection, and data analysis.

Research Approach

The methodological approach chosen to address the objective of this research is a systematic review, which is regarded as the most effective means to synthesize information from multiple research sources with similar research questions (Boland et al., 2017). There has been limited systematic reviews in social and environmental sciences despite the urgent need for a comprehensive synthesis of existing research and tools to evaluate progress within critical infrastructure and natural hazards research. The methodology is most commonly used to synthesize papers in health sciences; indeed, fewer than one percent of systematic review documents in the Web of Science database focus on areas outside of health sciences (Boland et al., 2017). A systematic review differs from a traditional literature review. It was chosen as the method for this study because it is designed to locate and synthesize the best available evidence related to a specific research question and assist in advancing a research field and making decisions around interventions and policy development and change.

Furthermore, systematic reviews follows a standard methodology to ensure they are reproducible, and they examine a collection of documents selected based on clearly defined and defensible criteria (Berrang-Ford et al., 2015; Boland et al., 2017). A systematic review follows a structured sequence of steps, which include: “a definition of the question or problem, identification and critical appraisal of the available evidence, synthesis of the findings and the drawing of relevant conclusions” (Boland et al., 2017, p.2). Additionally, they can reduce the number of sources of information and synthesize critical pieces of information to inform essential processes of decision-making, research and policy (Eckhardt et al., 2019).

In this study, the researcher followed a systematic review protocol pioneered by Boland et al. (2017), the process for which is laid out in Figure 1. This method was chosen to provide thorough guidance for conducting systematic reviews for Master’s theses and is informed by the systematic review process used in healthcare interventions with additional guidance for reviewing qualitative data (Boland et al., 2017).

Table 4: The main principles of systematically reviewing qualitative evidence (Boland et al., 2017)

Main Principles of Qualitative Synthesis	Description
1. Plan review	Planning review to understand how to best use time and resources available
2. Perform scoping searches, define review questions and inclusion and exclusion criteria, and write protocol	Carrying out scoping searches to help identify background literature will help you define and refine your review question and set your inclusion and exclusion criteria. A protocol must also be written which enables a researcher to set out the approach that will be used to answer review question(s)
3. Literature searching	Identifying evidence (published and unpublished) using bibliographic databases and other evidence sources that can be used to answer the research question(s)
4. Screening titles and abstracts	Reading titles and abstracts of the studies identified and discarding ones that are not relevant to the review question(s) and keep relevant ones
5. Obtaining papers	Obtaining full text-papers of the evidence identified in Step 4
6. Selecting full-text papers	Applying inclusion criteria to full-text papers and excluding ones that do not fit the criteria
7. Data extraction	Identifying relevant data from each paper and summarizing data using forms or tables
8. Quality assessment	Assessing each included full-text paper for methodological quality using an appropriate quality assessment tool
9. Analysis and synthesis	They are scrutinizing and synthesizing data, either narratively or through meta-analysis.
10. Writing up, editing, and disseminating	Writing up background, methods, and results, discussing findings, concluding the review, and disseminating findings.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method strengthens the validity and quality of the systematic review (PRISMA, 2020). The PRISMA method is a 27-item checklist intended to ensure the highest degree of transparency and quality reporting in qualitative research (Welch et al., 2016). Since the PRISMA method has had limited application outside of medical research and quantitative analysis, the researcher adapted the checklist based on its precepts and several recent papers which applied the qualitative analysis method for this study. The adapted version of the PRISMA method is provided below in Table 5 (Fayette & Bond, 2018; Moher et al., 2009;

Welch et al., 2016). The researcher utilized the guidance from Boland et al. (2017) to support the guidance of the overall methodological process. However, due to the centrality of the PRISMA approach among systematic reviews, the following section describes, in detail, each step outlined in the checklist provided above to ensure a high degree of transparency and quality reporting in this systematic review.

Table 5: PRISMA item checklist. Adapted from (Fayette & Bond, 2018; Moher et al., 2009; Welch et al., 2016) for a qualitative systematic review.

PRISMA Protocol for Qualitative Review in Social Sciences		
		TITLE
Title	1	Identify the report as a systematic review.
ABSTRACT		
Abstract	2	See the PRISMA 2020 for Abstracts checklist.
INTRODUCTION		
Rationale	3	Describe the rationale for the review in the context of existing knowledge.
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.
METHODS		
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.
Information sources	6	Specify all databases, registers, websites, organizations, reference lists, and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.
Search strategy	7	Present the complete search strategies for all databases, registers, and websites, including any filters and limits.
Selection process	8	Specify the methods used to decide whether a study met the review's inclusion criteria, including how many reviewers screened each record and each report retrieved, whether they worked independently, and, if applicable, details of automation tools used in the process.
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and, if applicable, details of automation tools used in the process.
Data items	10	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.
Synthesis methods	11	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).
	11a	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.
RESULTS		
Study selection	12	Describe the search and selection process results, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.
Results of syntheses	13	For each synthesis, briefly summarise the characteristics among contributing studies.
DISCUSSION		
Discussion	14	Provide a general interpretation of the results in the context of other evidence.
	15	Discuss implications of the results for practice, policy, and future research.

PRISMA Method Checklist

Step 7: Search Strategy

The researcher collected peer-reviewed journal articles for the systematic review from two research databases: Web of Science (Web of Science) and Scopus. The researcher selected the "all fields," selection and set the time period to 1900-2020. The initial search term of "critical infrastructure resilience" yielded 106 documents in Web of Science and 120 documents in Scopus (n=226). After removing duplicates, the final dataset before applying inclusion and exclusion criteria included 80 scholarly articles.

Table 6: Overview of the search strategy in Web of Science and Scopus

Database	Keywords Used	Search Results
Web of Science	"critical infrastructure resilience"	106
Scopus	"critical infrastructure resilience"	120
TOTAL		**226**

Step 8: Selection Process

The researcher vetted the scholarly articles for inclusion using the following criteria: (1) published in the English language; (2) peer-reviewed; and (3) linked to the research objective (i.e., the objective and findings of the research indicate that it is exploring, understanding, and analyzing one or more critical infrastructure sector(s) and indicate the exploration of the term 'resilience'). Studies excluded from the research study included the following criteria: (1) published in non-English language; (2) not published in peer-reviewed academic journals; and (3) not linked to the research objective (i.e., article purpose or findings did not offer important information or data to address any of the research questions). For example, some scholarly articles did not specify analysis of critical infrastructure sectors. Other articles did not mention exploring the term resilience and instead focused on terms such as 'safety' or ‘protection.’ Furthermore, some articles were highly technical. The researcher deemed their findings not relevant or substantial for inclusion in the dataset.

Table 7: A description of the inclusion and exclusion criteria applied to the initial set of articles

Inclusion Criteria	**Exclusion Criteria**
English language	Non-English language
Peer-reviewed journal article	Not a peer-reviewed journal article
Linked to the research objective	Not linked to the research objective

After applying the inclusion and exclusion criteria, 31 articles were not linked to the research objective; 5 articles were not published in peer-reviewed journals, and five articles were not available to the researcher to access. The final list of articles included in the research was 39. There is no consensus around the minimum number of papers that are ideal for a systematic review. However, Boland et al. (2017) suggested that if the searching, screening and selection processes have been rigorous, the researchers should feel confident that the final number of articles is sufficient for inclusion in the review. Figure 1 illustrates the search strategy and selection process executed for this research study.

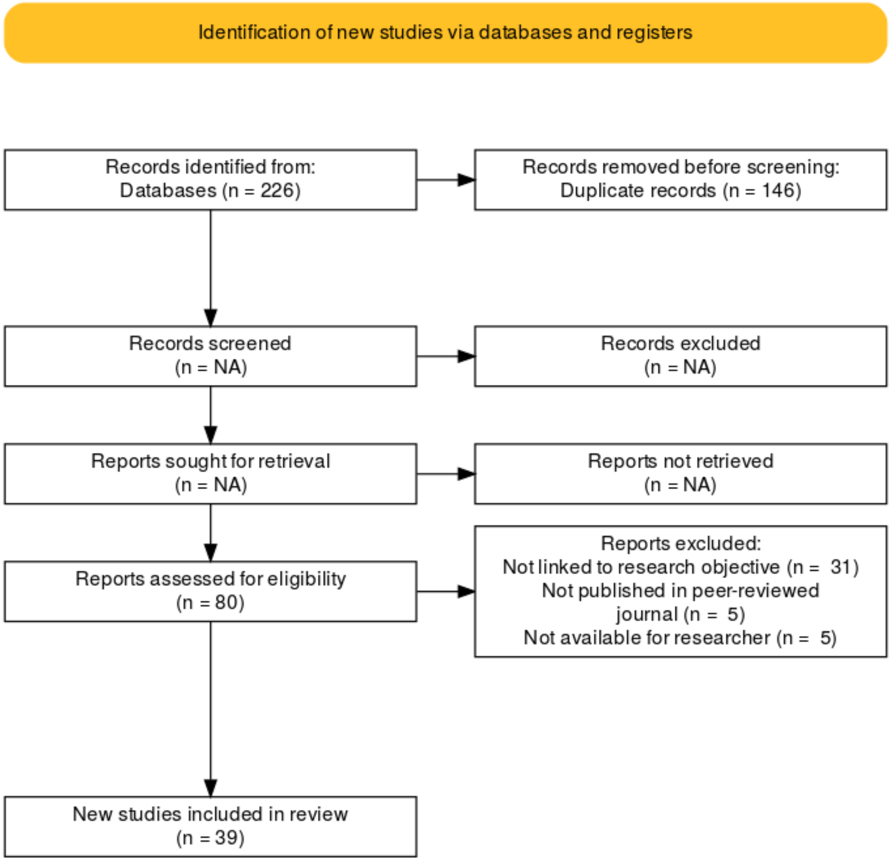

Figure 1: The PRISMA framework for selecting articles (Haddaway & McGuinness, 2020).

Step 9: Data Collection Process

The data from the articles were collected initially through independent data extraction. Independent data extraction involves identifying and extracting relevant data from the included papers and then storing it in a single format (a data table or form) (Boland et al., 2017). The individual researcher extracted data and recorded it into a Microsoft Excel spreadsheet. Independent data extraction indicates there was no second person to “cross-check” the data extraction and verify the data is accurate and complete (Boland et al., 2017). The individual researcher verified the data extraction as accurate and complete by setting the data extraction table aside for a week and completing the data extraction again to identify extraction errors or inconsistencies.

Step 10: Data Items

The data items extracted from each article included author, title; keywords; research problem; research problem; and principal findings and results. Additional data items extracted were publication year, study location, journal of publication; methodology; and research gaps outlined by the article authors.

Step 11: Planned Methods of Synthesis and Analysis

Descriptive and thematic content analysis of the data extracted was utilized to thoroughly analyze data, synthesize primary outcomes, draw vital common themes, and inform future research and practice. The descriptive and thematic analyses process consisted of four phases: reviewing the extracted data for common themes, developing a codebook, coding text excerpts, and identifying insights and themes across coded data.

Descriptive Analysis

A descriptive analysis provides a thorough descriptive account of the field of study for the reader to understand the research (Tranfield et al., 2003). The descriptive analysis clarifies the main characteristics of the articles in the dataset, such as methodologies used, study location and keywords (Lettieri et al., 2009).

Thematic Analysis

Thematic analysis is a method of organizing data and drawing insights from patterns in the data to identify key themes. It builds on the descriptive analysis as it provides more detail and a complex account of the data. A thematic analysis provides the reader with an overview of key themes and emergent themes as a means to report the state of knowledge in the field of study, and a central purpose is to inform a future research agenda (Braun & Clarke, 2012; Maguire & Delahunt, 2017; Tranfield et al., 2003). Themes identified as “key” or “emergent” in the thematic analysis process are determined based on their prevalence and frequency across the dataset and their relevancy and importance concerning research questions. This research followed established methods for inductive thematic analysis of qualitative research (Braun & Clarke, 2006, 2012) and guidelines for the thematic synthesis of qualitative research (Thomas & Harden, 2008)

Braun & Clarke (2006) provide a six-phase approach to thematic analysis, outlined in Table 8. Thomas & Harden (2008) provide guidance for a three-stage approach: 1) coding text; 2) developing descriptive themes, and 3) generating analytical themes (Thomas & Harden, 2008). As these approaches to thematic analysis are similar, the Braun & Clarke six-phase approach will be employed to ensure a robust and informed analysis of the data.

Table 8: The phases of thematic analysis (Braun & Clarke, 2006)

Phase		Description of Process
1.	**Familiarizing yourself with your data**	Reading and re-reading data, noting down initial ideas
2.	**Generating initial codes**	Coding exciting features of the data in a systematic fashion across the entire dataset, collating data relevant to each code
3.	**Searching for themes**	Collating codes into potential themes, gathering all data relevant to each potential theme
4.	**Reviewing themes**	Checking if the themes work in relation to the coded extracts (Level 1) and the entire dataset (Level 2), generating a thematic ‘map’ of the analysis
5.	**Defining and naming themes**	Ongoing analysis to refine the specifics of each theme and the overall story the analysis tells, generating clear definitions and names for each theme
6.	**Producing the report**	The final opportunity for analysis. Selection of vivid, compelling extract examples, the final analysis of selected extracts, relating the analysis to the research question and literature, producing a scholarly report of the analysis.

The Six Phases of Thematic Analysis

a) Data familiarization

The first step in the thematic analysis process is to become familiar with the data through repeated, active reading and taking notes that will support coding in the later steps (Braun & Clarke, 2006). To understand the data, the researcher read each journal article and noted the following information in a Microsoft Excel document: keywords, research problem, research objective, and research findings.

During the reading and note-taking, the researcher used an additional document to record patterns and observations from the data familiarization process to inform the subsequent steps.

b) Generating initial codes

Following the data extraction sheet review, the researcher employed a deductive approach to build a coding tree of semantic themes for qualitative content analysis in NVivo. The researcher used NVivo to upload the research articles, create and save nodes and categorize the data. Nodes are a collection of references referring to a specific theme, place, person or other area of interest (QSR International, 2021). After the researcher concluded the research questions, they derived several sub-research questions informing the broader coding tree in Appendix B. The researcher then read through each journal article and coded text sections that complied with the nodes developed. After reading, the researcher added codes inductively when a new code was needed to capture an essential or valuable piece of information (Braun & Clarke, 2012). The researcher deemed a new code essential or valuable if it contributed to any of the research questions presented. For example, while reading the articles, the researcher found several patterns within the terms used in the definition in resilience, so the node was revised with several sub-nodes to properly reflect these patterns (e.g., adaptation, recovery, disruption, and preparation). Another example of a revision is the initial sub-nodes for the node "types of resilience": ecological, engineering, complex adaptive systems, and social, determined based on the literature review. After reading the articles, the researcher found that these terms were not used to discuss types of resilience and revised the sub-nodes accordingly to social, technical, organizational, and economical.

c) Searching for themes

A key or emergent theme is determined through the prevalence and frequency within the dataset and captures something important concerning the research questions (Braun & Clarke, 2006). This phase requires analyzing the codes, identifying broader topics or issues and determining how the codes might be combined to form overarching themes (Braun & Clarke, 2012). The researcher reviewed all the coded data and identified similarities between codes. Similar codes were plotted in a thematic map and clustered based on an overarching theme.

d) Reviewing themes

The researcher refined the themes in two stages. First, the researched reviewed the coded data extracts to assess if they formed a coherent pattern. Their relevancy refined themes to research questions, the sufficiency and meaningfulness of data to support the theme, and data coherency to support the theme

(Braun & Clarke, 2012). Some themes did not have enough data to support them, and the researcher chose to not include them in the results. The researcher collapsed other themes into each other due to their similarity. The final review involved re-reading the data to ensure the themes identified meaningfully captured the data in a way that answered the research questions.

e) Defining and naming themes

This phase requires the final refinement of themes presented in the final analysis and data analysis within each theme (Braun & Clarke, 2006). The fundamental principles guiding this phase are ensuring the presented final themes: a) have a singular focus; b) are related but do not overlap so they are not repetitive; and c) directly address research questions (Braun & Clarke, 2012, p.66). The researcher reviewed the thematic map developed from the previous phases and determined which themes were most relevant to answer the research questions based on the principles provided above and identified the story each theme presented. The researcher used the frequency of coded text sections within each node as a critical determinant of relevancy in answering the research question. The final themes presented are the most commonly coded themes within the dataset. The final step in this phase was to determine the most relevant themes to present to ensure all research questions and review the themes to develop a coherent narrative presented in the Discussion chapter (Braun & Clarke, 2006, 2012).

f) Producing the report

The purpose of this phase is to present the analytical narrative of the dataset for the reader to ensure the merit and validity of the analysis with a concise, logical and exciting presentation of the data (Braun & Clarke, 2006). The final analysis and write-up of this thematic analysis is in the Results and Discussion chapters. These sections will outline the story of the data with sufficient and vivid examples of evidence to answer the research questions effectively.

Chapter 4: Results

This chapter presents the results of the systematic review. The first part of the chapter is the descriptive analysis providing an overview of the general parameters of the dataset. The second part of the chapter provides an overview of the major themes derived from the dataset to provide an in-depth understanding of the current state of knowledge and extant research findings of critical infrastructure resilience. Following the methodology described in the previous chapter, the significant themes described in Part 2 are based on the coding tree in Appendix C and were the most frequently discussed themes.

4.1 Descriptive Analysis

This section describes the methodological characteristics of the articles in the dataset. The characteristics of the articles in the dataset are the following:

1) Research peculiarities, objectives and keywords
2) Publication date
3) Study locations
4) Journal types
5) Research methodologies

Each of these characteristics is discussed in detail in the following five sections of the Descriptive Analysis sub-section.

1. Table 9 is a collection of all of the papers included in the review with the following details recorded:

- Author(s)
- Title
- Year
- Research Overview
- Keywords

This table provides an overview of all details of the dataset that was used to inform the coding and analysis.

Table 9: Summary of study qualities, descriptions and research overview of all articles included in the dataset

Number	Authors	Title	Year	Research Overview	Keywords
1	Applegate, CJ; Tien, I	Framework for Probabilistic Vulnerability Analysis of Interdependent Infrastructure Systems	2019	This paper applies a novel framework to model interdependent water and power infrastructure networks.	
2	Bloomfield, RE; Popov, P; Salako, K; Stankovic, V; Wright, D	Preliminary interdependency analysis: An approach to support critical-infrastructure risk-assessment	2017	This paper presents a methodology to analyze the interdependencies between CI.	Interdependency analysis, risk assessment, cascading failure, CIR
3	Boin, A; McConnell, A	Preparing for CI Breakdowns: The limits of crisis management and the need for resilience	2007	This paper presents a set of strategies for citizens, front-line workers and CI owners/operators to enhance societal resilience following a disaster.	
4	Brown, C; Seville, E; Vargo, J	Measuring the organizational resilience of critical infrastructure providers: A New Zealand case study	2017	This paper presents a methodology to assess the organizational resilience of CI providers using a case study in New Zealand.	Organizational resilience, CIR, Benchmarking resilience, measuring resilience, resilience indicators
5	Cedergren, A; Johansson, J; Hassel, H	Challenges to critical infrastructure resilience in an institutionally fragmented setting	2018	This paper explores the implications of a CI organization following disturbances in a multi-organizational setting impacted by deregulation using a case study of the Swedish railway system.	CI, resilience, recovery, institutional fragmentation, deregulation, contracts

6	Clark, S.S., Seager, T.P., Chester, M.V.	A capabilities approach to the prioritization of critical infrastructure	2018	This paper aims to demonstrate the use of a capabilities approach to determine the criticality of CI and argue that the most critical CI are the ones that are essential for providing or supporting human capabilities.	CI, Infrastructure services, capability approach, human development, infrastructure criticality, Maslow's hierarchy of needs
7	Comert, G; Pollard, J; Nicol, DM; Palani, K; Vignesh, B	Modelling Cyber Attacks at Intelligent Traffic Signals	2018	This paper presents a model to quantify the impacts of cyber--attacks on intelligent traffic signal components.	
8	Croope, SV; McNeil, S	Improving Resilience of Critical Infrastructure Systems Postdisaster Recovery and Mitigation	2011	This paper presents a framework (Critical Infrastructure Resilience Decision Support System) that models all the variables involved in improving CI resilience and seeks to reduce the vulnerability by offering insight into the trade-offs and opportunities involved to reduce damage and costs following a disaster.	
9	Curt, C; Tacnet, J-M	The resilience of CI: review and analysis of current approaches	2018	This paper is a literature review that presents the different dimensions of resilience, the current limitations to assessing and managing resilience and proposes future research directions to improve the field of resilience management.	CI, disaster, resilience
10	Cutts, M; Wang, YM; Yu, QS	New Perspectives on Building Resilience into Infrastructure Systems	2015	This paper presents the 2014 Cascadia Earthquake Readiness Workshop findings with government and industry individuals to examine new perspectives to improve resilience in critical infrastructure systems in the Pacific Northwest region.	
11	de Bruijn, KM; Maran, C; Zygnerski, M; Jurado, J; Burzel, A; Jeuken, C; Obeysekera, J	Flood Resilience of Critical Infrastructure: Approach and Method Applied to Fort Lauderdale, Florida	2019	This paper demonstrates how a discussion between government employees, research agencies, CI operators and managers and shared insights can improve resilience through developing a shared understanding of CI disruption and collaboratively developing solutions and introducing a novel indicator of resilience: "person disruption days."	resilience, flood risk management, critical infrastructure
12	Dick, K; Russell, L; Dosso, YS; Kwamena, F; Green, JR	Deep Learning for Critical Infrastructure Resilience	2019	This paper applies deep learning and machine vision as possible technological solutions to improve CI resilience.	
13	Dormady, N; Roa-Henriquez, A; Rose, A	Economic resilience of the firm: A production theory approach	2019	This paper applies a framework to an organization to improve its resilience to supply shortages and price changes to provide a basis for analyzing large-scale supply chain resilience.	Economic resilience, production theory, inherent and adaptive resilience, disasters

14	Egli, DS; Donohue, BH; Waddell, RL; Contestabile, JM; Cosgrove, JB	Operationalizing Critical Infrastructure Resilience	2019	This paper presents a qualitative framework for CI resilience which is meant to inform local and regional planners and government officials and the private sector to ensure broader and holistic community resilience.	
15	Espada, R; Apan, A; McDougall, K	Vulnerability assessment of urban community and critical infrastructures for integrated flood risk management and climate adaptation strategies	2017	This paper presents a quantitative framework integrating disaster risk reduction and climate adaptation to assess flood risk on CI and improve flood risk management issues.	Risk analysis, infrastructure, vulnerability, flooding, built environment, capacity
16	Fang, YP; Sansavini, G	Optimum post-disruption restoration under uncertainty for enhancing critical infrastructure resilience	2019	This paper presents a quantitative model which can assess the repair time and resources required to improve the resilience CI and is demonstrated through the case study of the British electric power system.	CI, system resilience, restoration planning, uncertainty, stochastic programming
17	Fekete, A	CI and flood resilience: cascading effects beyond water	2019	This paper presents a framework that integrates disaster risk management and CI resilience concepts	CI, disaster resilience, flood management, flood risk, flood risk management
18	Garschagen, M; Sandholz, S	The role of minimum supply and social vulnerability assessment for governing critical infrastructure failure: current gaps and future agenda	2018	This paper investigates how the assessment and mitigation of social vulnerabilities and the implementation of minimum supply standards for CI can reduce the negative impacts of CI disruption.	
19	Johansen, C; Tien, I	Probabilistic multi-scale modelling of interdependencies between critical infrastructure systems for resilience	2018	This paper analyzes the interdependencies between CI to understand better how to restore services and result in fewer damages using a novel Bayesian network model.	CIR, interdependencies, Bayesian networks, probabilistic modelling, risk assessment
20	Kozine, I.O; Trucco, P; Petrenj, B	Resilience capacities assessment for critical infrastructures disruption: the READ framework (part 1)	2018	This paper presents a capabilities-based framework for improving the resilience of CI.	CI, resilience assessment, capability-based planning, emergency management, public-private partnership, gap analysis
21	Krishnamurthy, V., Huang, B., Kwasinski, A., Pierce, E., Baldick, R.	Generalized resilience models for power systems and dependent infrastructure during extreme events	2020	This paper presents a quantitative framework to assess the resilience of CI. It focuses specifically on assessing electrical power and telecommunications due to its high criticality during extreme events.	
22	Labaka, L; Hernantes, J; Sarriegi, JM	A holistic framework for building critical infrastructure resilience	2016	This paper presents a novel qualitative framework for improving the resilience of CI with detailed prescriptions for various stakeholders such as CI operators, government officials, emergency responders and other external agents.	Crisis management, CI, resilience, resilience policies, Delphi process, case studies

23	McDonald, M; Mahadevan, S; Ambrosiano, J; Powell, D	Risk-Based Policy Optimization for Critical Infrastructure Resilience against a Pandemic Influenza Outbreak	2018	This paper presents a decision-making model using system dynamics to model different scenarios following a pandemic influenza outbreak.	
24	Murdock, HJ; de Bruijn, KM; Gersonius, B	Assessment of Critical Infrastructure Resilience to Flooding Using a Response Curve Approach	2018	This paper presents a quantitative method for assessing CI resilience based on several novel indicators in Toronto, Canada.	Resilience, CI, quantifications, impact assessment, risk reduction, flood risk
25	Nazarnia, H; Sarmasti, H; Wills, WO	Application of household disruption data to delineate critical infrastructure resilience characteristics in the aftermath of a disaster: A case study of Bhaktapur, Nepal	2020	This paper presents a novel framework for assessing resilience quantitatively using CI service disruption data and applies it to a case study in Bhaktapur, Nepal	Resilient city, disaster resilience, disruption data, civil infrastructure systems, emergency response
26	Ouyang, M; Chuang, L; Min, X	Value of resilience-based solutions on critical infrastructure protection: Comparing with robustness-based solutions	2019	This paper compares four mathematical models to quantify the difference in implementing resilience-based solutions vs. robustness-based solutions for CI	CIP, robustness, resilience, worst-case malicious attack, natural hazards
27	Pant, R; Thacker, S; Hall, J.W.; Alderson, D; Barr, S	CI impact assessment due to flood exposure	2018	This paper presents a quantification of CI resilience to flooding using the indicator of disrupted customers due to direct impact (i.e. electricity customer dependent on electricity asset) and disrupted customers due to indirect network impacts (i.e. telecommunications customer dependent on electricity assets)	CI, customer disruptions, flood catchment, flood hazard, infrastructure networks, risks, vulnerability
28	Pursiainen, C	Critical infrastructure resilience: A Nordic model in the making?	2018	This paper analyzes the strategic approach to CI resilience in four Nordic countries (Denmark, Finland, Norway and Sweden) and highlights the everyday trends and differences.	CI, resilience, civil protection, crisis management, the Nordic model
29	Rachunok, B; Nateghi, R	The sensitivity of electric power infrastructure resilience to the spatial distribution of disaster impacts	2020	This paper demonstrates the use of a quantitative metric (spatial distribution of disasters) to assess the resilience of CI.	
30	Ridley, G	National Security as a Corporate Social Responsibility: Critical Infrastructure Resilience	2011	This paper argues that CSR researchers and practitioners should extend the scope of CSR research to incorporate CI resilience and acknowledge that due to the large-scale privatization of CI, the resilience of CI is a significant modern CSR issue.	British railway industry, case study, corporate social responsibility, critical infrastructure resilience, essentially contested concepts, Microsoft Corporation, national security
31	Robert, B., Morabito, L., Cloutier, I., Hémond, Y.	Interdependent critical infrastructures resilience: Methodology and case study	2015	This paper presents a novel qualitative approach (coherence analysis) to assess the resilience of CI.	Case study, resilience, coherence analysis, CI, protection, hazards
32	Rod, B; Lange, D; Theocharidou, M; Pursiainen, C	From Risk Management to Resilience Management in Critical Infrastructure	2020	This paper builds on existing risk management standards to incorporate CI resilience and	CI, organizational resilience, technological resilience, societal

				presents a more standardized approach to improving CI resilience.	resilience, risk management, resilience measurement, resilience assessment, resilience analysis, resilience evaluation
33	Roe, E; Schulman, P.R	Toward a comparative framework for measuring resilience in CI systems	2020	This paper presents a quantitatively assessing resilience in communities to allow for comparative assessment of risks between different sectors and communities.	
34	Rogers, P.	Development of Resilient Australia: Enhancing the PPRR approach with anticipation, assessment and registration of risks	2011	This paper presents the Australian approach to enhancing CI resilience, contrasts it with the UK model and highlights the importance of building on the current strategy in Australia instead of replacing it.	
35	Serre, D; Heinzlef, C	Assessing and mapping urban resilience to floods for cascading effects through CI networks	2018	This paper presents new methods to assess the resilience of CI to flooding in urban environments.	Urban flooding, critical infrastructure networks, cascading effects, resilience strategies, climate change
36	Tonn, G; Czajkowski, J; Kunreuther, H; Angotti, K; Gelman, K	Measuring Transportation Infrastructure Resilience: Case Study with Amtrak	2020	This paper presents a case study conducted with representatives of Amtrak (a US passenger rail service) in which the representatives reviewed metrics of resilience and selected resilience activities to serve as the baseline for assessing the organization's resilience.	
37	van der Merwe, S.E., Biggs, R., Preiser, R.	Sensemaking as an approach for resilience assessment in an Essential Service Organization	2020	This paper presents a novel indicator for assessing CI resilience within an organization through the qualitative measurement of employee's "sense of coherence."	CIR, general social resilience, sensemaking, sense of coherence, resilience capacities, emergency exercise
38	Wei, D; Chen, ZH; Rose, A	Evaluating the role of resilience in reducing economic losses from disasters: A multi-regional analysis of a seaport disruption	2019	This paper presents a framework for the quantitative assessment for the resilience of CI following the implementation of various resilience tactics.	computable general equilibrium analysis, economic consequence analysis, port disruptions, resilience to disasters, spatial reallocation of resources
39	Zimmerman, R; Zhu, QY; de Leon, F; Guo, Z	Conceptual Modeling Framework to Integrate Resilient and Interdependent Infrastructure in Extreme Weather	2017	This paper presents a framework for assessing the resilience of CI and, specifically, how interdependencies and dependencies influence outcomes using the indicator of recovery time.	

1. Publication Date

Figure 2 provides a depiction of the publication years of the papers included in the review. Although the initial search timeframe was from 1900 to 2020, the final papers' timeframe is from 2006 to 2020. The highest number of publications in this review was in 2018 (n=12), and numbers decrease slightly in the following years. The results indicate that research surrounding critical infrastructure resilience is a relatively new concept in scholarly literature and is still emerging. The increased discussion in the academic literature of the concept in recent years is likely due to the realization among governments and academic scholars that resilience of CI is necessary to national security and development. For example, the Organization for Economic Co-operation and Development (OECD) has published several reports declaring the importance of critical infrastructure resilience as historic critical infrastructure policies have not always been effective in challenging the increasingly complex and interconnected global landscape of risk. Their reports provide insight into the changing risk landscae and provide guidance for improving CI resilience globally (OECD, 2019). Furthermore, prevailing threats such as climate change and natural disasters, advanced technology and cyber-attacks, and the severity of CI failures and disruptions have drawn the attention of scholars towards CI resilience (Osei-Kyei et al., 2021). The acknowledgement that society’s require CI resilience to ensure social, health and economic wellbeing paired with the knowledge of the uncertainty of future risks from threats will contribute to the projected increase in research studies and scholarly literature of this concept in the coming years (Canada, 2021; OECD, 2019; Osei-Kyei et al., 2021).

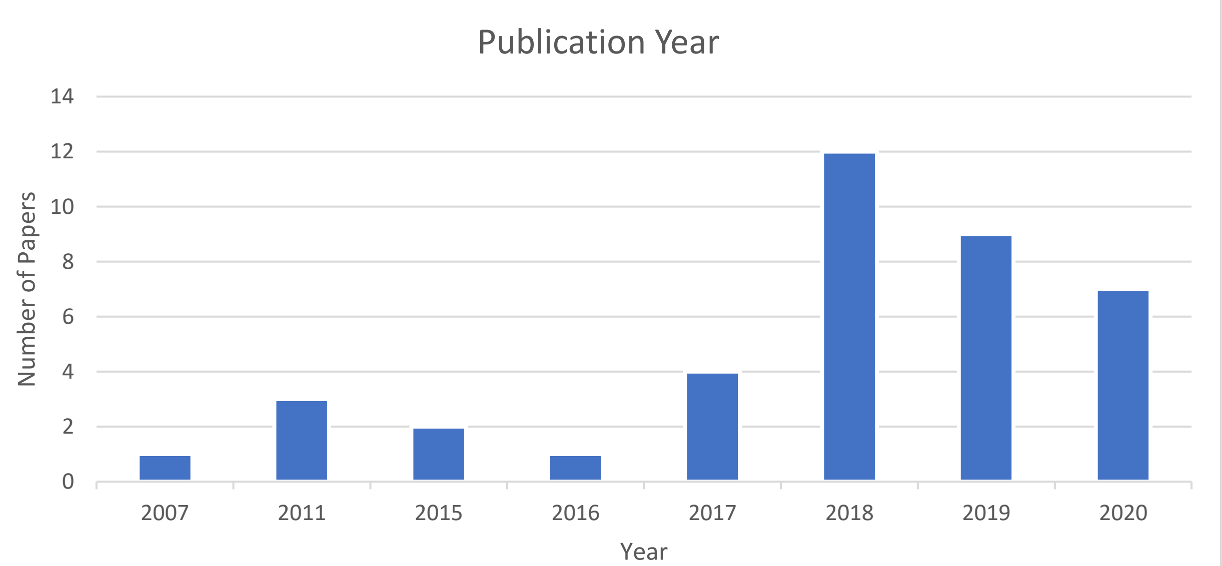

Figure 2: A spread of the articles included in this review within the time period of 1900-2020

2. Study Location

Figure 3 depicts the study location of the papers included in this review. Twenty-four papers provided a specific geographic location for the research focus or a case study within the sample. The study location of the papers in this review focuses significantly on the Global North and specifically in North America. The United States was the most commonly chosen study location for papers (n=8). The prevalence of research studies in the United States is likely due to their interest in protecting CI in the early 21st century. The U.S. published its strategies and policies for CI protection in the late 1990s and indicated an increased interest following the 9/11 terrorist attacks, the Northeast blackout in 2003 and Hurricane Katrina in 2005 (Petit et al., 2013).

Furthermore, after the United States published its strategies, other developed countries such as Canada and various countries in the European Union (EU) followed shortly through the National Atlantic Treaty Organization (NATO) and then through the EU following the 2004 Madrid and 2005 London terrorist attacks (Pursiainen, 2018). Only one paper in the sample had a study location that was not a developed country (Nepal). Although there is no evidence to corroborate precisely why there is limited research around CI resilience in developing countries, it could be since there is limited political and institutional development of CI resilience strategies in those countries or that many of the papers are published in non-English journals or journals that are not indexed in the Scopus and Web of Science databases (Osei-Kyei et al., 2021). The limited research in developing countries might also indicate that the concept is still undergoing academic development in those regions and will likely lead to future research to better understand how CI resilience applies in those contexts. likely lead to future research to better understand how CI resilience applies in those contexts

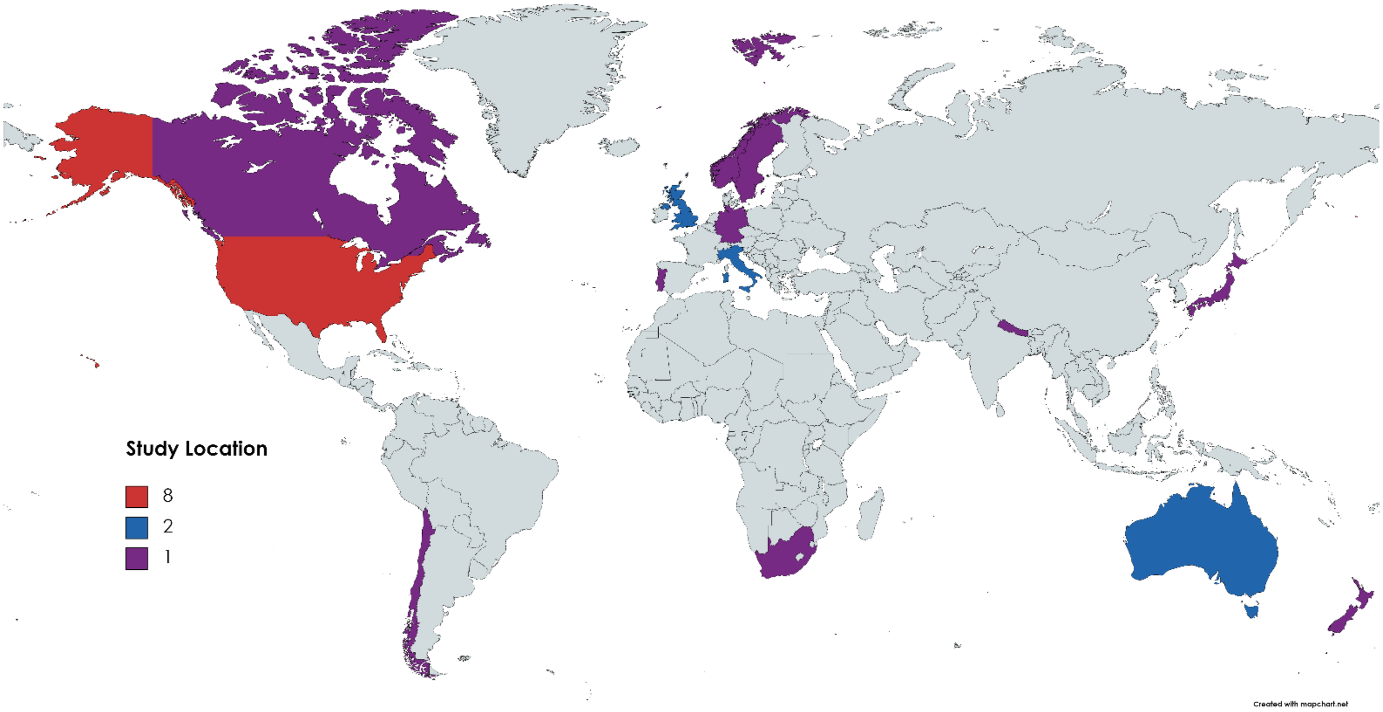

Figure 3: Classification of papers according to the country of origin of their study location

3. Research Field & Journal Type

Figure 4 depicts the classification of the papers in the review based on the research field. The researcher derived the fields from reviewing the descriptions of the journal of publication to identify the parameters used by editors to solicit article submissions. The findings suggest that a large proportion of papers remain focused on the engineering field (n=12). Following engineering, human geography (n=7) and disaster management (n=5) had the second and third, respectively, the highest number of papers in this study. Furthermore, additional fields include political sciences (n=2), natural hazards (n= 3), transportation (n=3), environmental sciences (n=3), crisis management (n=3) and business and economics (n=2). Within engineering, the most common sub-fields include civil engineering (n=7), reliability engineering and systems safety (n=3), industrial engineering (n=2) and electrical engineering (n=1).

The findings suggest that although the most significant number of papers concentrates on the engineering research field, researchers from other fields also study critical infrastructure resilience, and the concept is interdisciplinary. This finding indicates that the concept might continue to be studied across various research disciplines, bringing additional perspectives to further advance knowledge and provide a more holistic understanding of the concept.

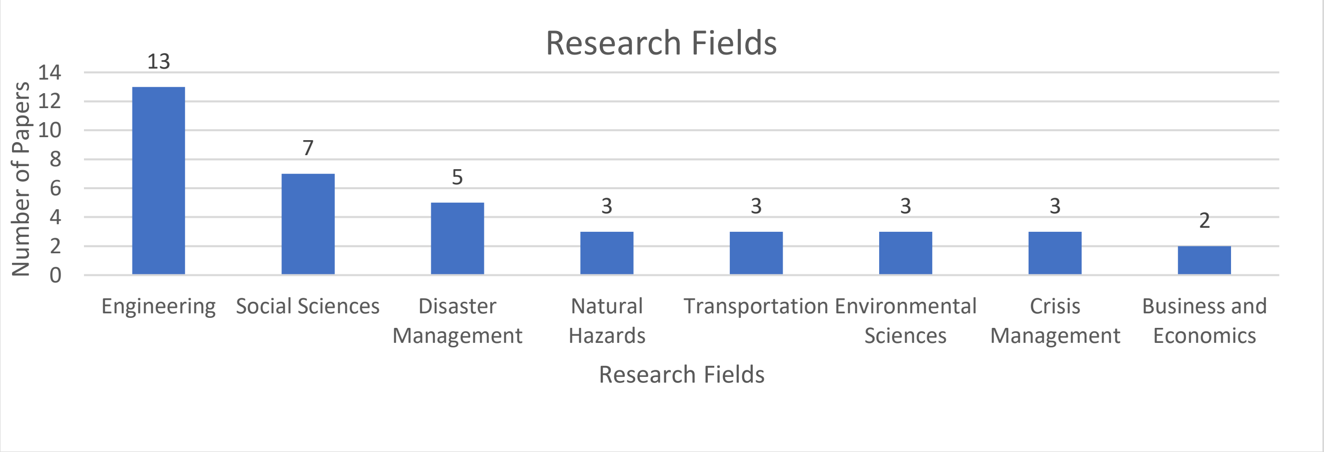

Figure 4: Classification of the included articles according to the research field determined by the journal of publication

4. Methodology

This section depicts the classification of the paper's methodology in this review (see Figure 5)—an almost equal number of papers utilized either quantitative (n=17) or qualitative (n=16) methodology. Most papers (n=13) using a quantitative methodology developed and applied a framework with the goal of either assessing CI resilience or enhancing it. In addition, several papers using quantitative methodologies identified specific indicators which were applied to assess CI resilience or used a Bayesian network approach to model infrastructure interdependencies or modelling the impacts of cyber-attacks on transportation technology. There is significantly more variation between the papers using qualitative methodology, but several frameworks utilize qualitative components to assess or enhance CI resilience. In addition, several papers adopted a case study approach by assessing CI resilience policies or strategies in countries such as Australia, New Zealand, and the Nordic countries. There was a much smaller proportion of papers that used a mixed methodology (n=6). The papers utilized mixed methodologies were all published within the last ten years, indicating a more recent evolution into combining qualitative and quantitative methods to assess or enhance CI resilience. Furthermore, these papers combined methodologies to assess interdependencies between CI, vulnerabilities in infrastructure systems or CI resilience. There was one paper that combined qualitative knowledge with the first quantitative indication of resilience to improve CI resilience

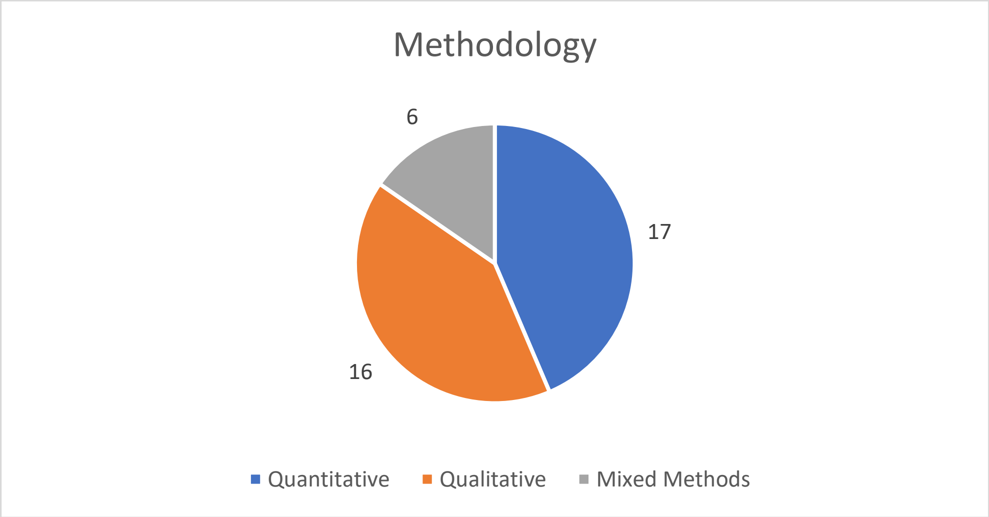

Figure 5: Classification of articles included in this review based on the research methodology used

Descriptive Analysis Conclusion

In conclusion, the descriptive analysis provided several insights surrounding the publication date, study location, research field and methodology of critical infrastructure resilience research. Two key insights emerged from the descriptive analysis. Firstly, the majority of research is focused within the last decade indicating the relatively recent emergence of the topic. Furthermore, the results indicate there is an acknowledgement that society’s require CI resilience to ensure social, health and economic wellbeing paired with the knowledge of the uncertainty of future risks from threats will contribute to the projected increase in research studies and scholarly literature of this concept in the coming years. Second, the research results indicate that there is a lack of research with study locations outside of the Global North. The limited research in developing countries indicates that the concept is being academically developed in those regions and will likely lead to future research to better understand how CI resilience applies in those contexts.

4.2 Thematic Analysis

This section presents and describes the major themes identified within the dataset and the research objectives and findings of the 39 articles included in the dataset. The following guiding research questions, which were developed based on the broader research questions and the literature review, to guide the development of the codebook and to conduct the analysis and results.

Table 10: Guiding research questions developed from the literature review

Guiding Research Questions
How is CI resilience being defined?
How is resilience being measured and assessed?
What are the objectives for CI resilience? Is it to assess or enhance resilience?
What type of resilience is being discussed? Ex. Engineering, ecological, social
What frameworks for CIR are discussed? Are they theoretical or implemented case studies?
What models are discussed? Are they quantitative or qualitative? Are they applied or theoretical?
What are the case studies conducted in the research?
How is vulnerability being defined and framed? Ex. Social vulnerability
What indicators are being used to measure resilience?
What risks to CIs are being discussed? Is it an all-hazard or fragmented approach?
What geographic regions are analyzed in studies?
How are interdependencies/dependencies assessed? Ex. cascading failures.

The codebook was developed, guided by the “developing initial codes” step in the Six Phases of Thematic Analysis (see Methods chapter). The following codebook is the final codebook, revised during the coding step. The initial codebook was developed following the development of the guiding reserch questions, which is provided in Appendix A. The codebook was analyzed to identify major themes which are described in detail in the following section.

Codebook

Table 11: The final codebook developed based on the guidance from The Six Phases of Thematic Analysis

Node	Sub-nodes
Adaptive capacity	
Assessing criticality	
Barriers to resilience	
Business continuity	
Resilience definition	Adaptation Disruption Recovery Preparation
Measuring resilience	
Assessing resilience	
Enhancing resilience	Capabilities approach Public policy tools Technical solutions
Disaster management	Flood risk management Disaster assessment
Types of resiliency	Social Technical Organizational Economic
Frameworks	Theoretical Empirical
Models	Theoretical Empirical
Case studies	
Vulnerability definition	Exposure Hazard
Resiliency indicators	
Hazards (to CI)	Flooding Terrorism All-hazard
Study location	Canada US Europe Africa Asia Australia/New Zealand
Interdependencies/dependencies	Cascading failures
Recovery	
Research gaps	
Risk management	
Stakeholders	CI owners/operators

	Governments Policymakers Practioners
Environments	Urban Rural
Climate change	
Types of infrastructure	Communication Energy Financial Public Health Stormwater Transport Water

This section is divided into two parts. The first part describes the major themes in the concepts of CI resilience, and the second part describes the major themes across the articles' research objectives and findings which were developed by reviewing the codebook. Both sections begin with a description of the number of articles with content coded within each theme.

4.2.1 Themes among CI Resilience Concepts

To identify the major themes, a thematic analysis was followed (see Methodology). This section describes the four major themes surrounding the conceptualization of CI resilience which includes:

1) Defining CI resilience (n=29);
2) Types of CI (n=29)
3) Risks to CI (n=23); and,
4) Types of CI resilience (n=16)

1. Defining Resilience

A lack of understanding of “critical infrastructure resilience” has led to criticism that without an established definition, widespread use of the term has made it too vague and difficult to operationalize (Cedergren et al., 2018; Moteff et al., 2003; Rogers, 2011). Overall, there is some consistency between definitions of resilience within the dataset but remains closely linked to 19th century perspectives from material physics and engineering. There is some indication within the dataset that there is an evolution from the original definition to one that more closely reflects societal resilience emerging from research on complex adaptive systems. However, it is not consistent across the CI resilience literature.

The most commonly incorporated term across the dataset is “recover” (n=19) closely resembling the following example: “resilience is the ability to withstand and recover rapidly from disruptions” (Krishnamurthy et al., 2020, p.194). The second most referenced term across the dataset is “adapt” (n=17). For example, a commonly used definition for resilience across the dataset is “the ability to adapt to changing conditions and withstand and rapidly recover from disruptions due to emergencies” (Egli et al., 2019, p.424). Similarly, the colloquial phrase “bounce back” is used across the data et (n=2), such as “the ability to ‘bounce back’ after suffering a damaging blow’ (Boin & McConnell, 2007, p.54). The general resilience definitions related to recovery and “bouncing back” derives from the origin of resilience in material physics and engineering literature, defined as a physical structure’s ability to “bounce or spring back into shape or position after being pressed or stressed” (Egli et al., 2019, p.424). Most definitions across the dataset using the terms “adapt” and “recover” related to general resilience in nature. In contrast, a smaller portion are more specific to CI and refers to either a structure, system or function’s ability to adapt or recover from a disruption (Brown et al., 2017; Cedergren et al., 2018; Clark et al., 2018; Croope & McNeil, 2011; Curt & Tacnet, 2018; de Bruijn et al., 2019; Kozine et al., 2018; Serre & Heinzlef, 2018).

Definitions that refer to a structure, system, or function’s ability to adapt or recover are already more context-specific to CIs and enable better operationalization of the term such as in the example: “resilience is the ability of a system to adjust its functioning before, during or following changes and disturbances so that it can continue to perform as required after a disruption or a major mishap, and in the presence of continuous stresses (Cedergren et al., 2018, p.53). Furthermore, Egli et al. (2019) state that resilience is about adapting to and recovering from disruption and improving and getting stronger following an adverse event. Despite this necessary component to resilience, terms related to improvement post-disruption such as “repair,” “rebuild,” “reconstruction,” “growth,” and “transformation” are only referenced in four articles in the dataset (Dormady et al., 2019; Egli et al., 2019; Fang & Sansavini, 2019; Rød et al., 2020). For example, Rod et al. (2020) defined resilience as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to transform and recover from the effects of a hazard” (p.2). Egli et al., (2019) highlighted that resilience is also “the ability to get stronger as a result of adversity and the chance to rebuild out systems so that they have greater functionality and efficiency” (p. 424).

Despite the necessity of planning for effective resilience practices, the literature only references the terms “prepare” and “plan” in eight articles in the dataset (Applegate & Tien, 2019; Brown et al., 2017; Curt & Tacnet, 2018; de Bruijn et al., 2019; Johansen & Tien, 2018; Kozine et al., 2018; Krishnamurthy et al., 2020; Murdock et al., 2018). Curt & Tacnet (2018) provided a definition that encompasses all four components by asserting resilience involves four capacities: “to plan and prepare for the adverse events, to reduce the impact of events, to minimize the time to recovery and to evolve through the development of specific processes (Curt & Tacnet, 2018, p.2443). Similarly, de Bruijn et al. (2019) described a resilient system as one that can: “1. prevent frequent events from causing negative impacts; 2. mitigate impacts of rare events, so they do not become disastrous; 3. easily recover from impacts; 4. learn from events, adapt to changes, and maintain their ability to cope with disturbances also in the future.” (de Bruijn et al., 2019, p.3). Kozine et al. (2018) is the only other article in the dataset to include the four components for resilience.

Clark et al., (2018) is critical of narrow descriptions of resilience noting that definitions that emphasize the physical condition of infrastructure are not referencing resilience. Rather, they argued that resilience should be related to the vital services provided by the physical infrastructure. It should clarify human development as critical infrastructure’s primary purpose is to provide essential services to society. Throughout the dataset, five articles refer to the importance of providing essential services when determining resilience (Clark et al., 2018; Comert et al., 2018; Pursiainen, 2018; Roe & Schulman, 2012; van der Merwe et al., 2020). Notably, Nordic countries' CI resilience policies focus on CI's vital societal functions instead of protecting physical infrastructure. For example, Finland’s approach to resilience of CI emphasizes the assurance that society and the government can function during a disruption or extreme event and not the protection of physical infrastructure (Pursiainen, 2018). Norway’s perspective on CI resilience builds on this idea even further as it clearly defines the most vital societal functions as those that “society could not cope without for seven days or less” (Pursiainen, 2018, p.634).

Overall, it is evident that the definition of resilience remains more closely linked to the original understanding from the engineering field and emphasizes the protection of and minimization of impacts on physical structures. As described in Chapter 2, engineering resilience does not capture the complexity of CI. It requires a more robust definition and should capture both pre-and post-data (instead of focusing on only pre-disaster data to understand exposure and sensitivity), focus on minimizing impacts (instead of preventing them) and seek to improve the ability of the system(s) to cope with and recover from future unanticipated crises or disasters (instead of attempting to predict the frequency and magnitude of events).

2. Types of Resilience

Critical infrastructure resilience has historically centred on the idea of protecting physical assets, but several studies in the dataset identified different types of resilience. There is still an over-emphasis on technical resilience within the dataset despite advocacy within the literature to focus on societal resilience. Interestingly, there has been an emergence of organizational and economic resilience, which reflects the transition of CI out of the public realm and indicates some acknowledgement from private sector actors that they must also understand and improve CI resilience.

Technical resilience appeared the most often across the dataset, which is described as the improvement of the physical infrastructure's resistance to damage and its ability to perform when faced with disruption (Egli et al., 2019; Fekete, 2019; Labaka et al., 2016; Pursiainen, 2018, 2018; Ridley, 2011; Rød et al., 2020; Serre & Heinzlef, 2018; Tonn et al., 2020; van der Merwe et al., 2020). Serre & Heinzlef (2018) analyzed the technical resilience of systems in an urban setting by analyzing their abilities to absorb and recover from a disturbance. The authors posited that the resilience of an urban environment is highly dependent on the resilience of its technical systems and their ability to maintain functions following a significant disruption (Serre & Heinzlef, 2018). The dominance of technical resilience in current literature is due to the origin of CI research in the engineering field and the focus on protection of physical assets (Fekete, 2019). Organizational resilience appeared in five articles in the dataset (Brown et al., 2017; Labaka et al., 2016; Pursiainen, 2018; Ridley, 2011; Rød et al., 2020; Serre & Heinzlef, 2018).

Organizational resilience is an emerging field and refers specifically to an organization's capacity to adapt to and recover from a crisis (Brown et al., 2017; Labaka et al., 2016). Ridley (2011) presented a perspective on organizational resilience, which discussed the extension of corporate social responsibility to include critical infrastructure resilience due to national and global security concerns. Private owners increasingly control critical infrastructure in Western countries. Although organizational resilience is an emerging field, it may become more relevant to explore CI research if CI ownership remains dominated by the private sector. If private actors are the primary owners and operators of CI, they will inherently hold the responsibility of ensuring its resilience because they provide vital services to society. The literature alludes to the conclusion that despite the transition of CI from the public sector to predominately within the private sector, limited research has been conducted to analyze organizational resilience of CI despite its importance and necessity.

Several papers discuss economic resilience (n=3). It is closely related to organizational resilience but focuses specifically on economic dimensions, such as the efficient use of resources, coping with resource scarcity during crises and investing resources in repair and reconstruction (Dormady et al., 2019; Labaka et al., 2016; Murdock et al., 2018). Dormady et al. (2019) presented a framework applying economic resilience in a microeconomic context by applying a Constant Elasticity of Substitution Function, which calculates the effectiveness of various individual tactics within one CI organization but could be scoped to a macroeconomic focus as well. Additionally, economic resilience addresses the need to reduce the loss of goods and services from a disrupted infrastructure and more closely aligns with complex adaptive systems resilience. In contrast, engineering resilience focuses on reducing physical damage (Dormady et al., 2019).

Four articles in the dataset discussed societal resilience (Clark et al., 2018; Labaka et al., 2016; Murdock et al., 2018; Pursiainen, 2018). Societal resilience is the use of social capital and networks to reduce losses and impacts from the disruption to critical infrastructure and, despite the limited research in CI literature, has significant potential to play a critical role in overall CI resilience (Clark et al., 2018; Labaka et al., 2016). Clark et al. (2018) presented research that suggests communities with high social capital perform better following a disaster since they can self-organize and provide help to community members and, consequently, have higher survival rates and faster recovery. Furthermore, Labaka et al. (2016) explored several non-technical solutions which coincide with societal resilience such as developing trusted network communities to gather and share information as well as the preparation of surrounding populations to ensure they are prepared for any crises that could occur. Societal resilience identifies responsibilities for all four stakeholders identified in Chapter 2 and the utilization of non-technical solutions, alongside technical solutions to improve CI resilience.

CI policies in Nordic countries are typically more focused on societal resilience and less focused on technological and organizational resilience since they focus more on the assurance that actors such as governments, communities and households remain resilient during disasters in comparison to businesses (organizational) or the safety and security of the physical infrastructures (technological). Pursiainen (2018) presented a Nordic model for critical infrastructure resilience, positing that Nordic countries (Denmark, Finland, Norway, and Sweden and excluding Iceland) are better equipped to address critical infrastructure disruptions and failures in comparison to the European Union (EU), because they prioritize societal resilience. Furthermore, the author argues Sweden was one of the first countries to prioritize societal safety and security in its national strategy for the protection of important public services, which defined resilience as “the capacity that society has to withstand and recover from disruption” (Pursiainen, 2018, p.635).

Four articles in the dataset discussed three or more types of resilience in detail (Labaka et al., 2016; Murdock et al., 2018; Pursiainen, 2018; Rød et al., 2020). Labaka et al. (2016) considered the importance of the four types of resilience (technical, organizational, economic, and social). The authors posit that adopting all four types can provide a more holistic and prescriptive approach to improving CI resilience. In conclusion, the literature indicates an over-emphasis on technical resilience even though there is a growing sentiment justifying a move towards societal resilience.

3. Risks and Hazards to Critical Infrastructure

To be effective, policies for CI resilience must consider a wide range of risks, including s non-physical risks (cyber-attacks, regulatory changes, privatization, fiscal austerity) since they can significantly affect CI (Brown et al., 2017). Overall, the literature in the dataset focuses primarily on physical threats, specifically natural hazards, and disasters. There is little discussion around non-physical threats, particularly the political threats to CI resilience.

The most discussed risks to CI across the dataset are natural hazards and disasters (n=10). Within the dataset, four articles focused explicitly on evaluating or improving resilience against disasters (Croope & McNeil, 2011; Nazarnia et al., 2020; Wei et al., 2019.; Zimmerman et al., 2017). The second most discussed physical risk across the dataset was floods (n=7), and the articles focused specifically on understanding or building resilience of CI to flooding (de Bruijn et al., 2019; Espada et al., 2017; Fekete, 2019; Murdock et al., 2018; Pant et al., 2018; Serre & Heinzlef, 2018; Zimmerman et al., 2017). Serre &

Heinzlef (2018) stated that floods are the costliest natural disaster globally, significantly increasing year over year. De Bruijn et al. (2019), Pant et al. (2018), and Fekete (2019) argued that there is a lack of assessment of flood impacts when understanding CI resilience due to insufficient research on the quantitative and qualitative costs of flooding to CI. Furthermore, cascading effects between CI demand a broader understanding of the damage that occurs, including hazard triggers like fires, oil spills, terror attacks, and others. Therefore, building CI resilience is a necessity for a community's overall resilience.

The third most discussed risk is earthquakes (n=4) (Brown et al., 2017; Cutts et al., 2017; Fang & Sansavini, 2019; Roe & Schulman, 2012). Cutts et al. (2015) conducted research using workshops to develop a plan that would improve the resilience of a region if an earthquake or tsunami occurred in the Pacific Northwest, which resulted in a framework that could be applied in any region as we all as other hazards. Fang & Sansavini (2019) proposed a multi-mode restoration model that addresses a gap in knowledge surrounding electrical power restoration following an earthquake.

Tsunamis are the next most discussed physical hazard (n=3) (Cutts et al., 2017; Roe & Schulman, 2012; Wei et al., 2019). Wei et al. (2019) presented two different quantitative models to estimate the economic consequences of a tsunami's disruption to a port and the port's resilience to a tsunami scenario in California. Only two articles in the dataset referenced terrorism as a risk to CI, which is interesting since the historical focus of national and regional CI policies was terrorism. These results further demonstrate the transition to a more holistic understanding of risks such as natural hazards and disasters (Bloomfield et al., 2017; Pursiainen, 2018). Additional risks to CI discussed were: climate change (n=3); cyber-attacks (n=3); pandemics (n=2); fires (n=1); and sea-level rise (n=1) ((Bloomfield et al., 2017; Clark et al., 2018; Comert et al., 2018; Fekete, 2019; McDonald et al., 2018; Pant et al., 2018; Tonn et al., 2020; Zimmerman et al., 2017).

There is a lack of substantive research across the dataset around climate change, sea-level rise, and fires. There is also little discussion in the dataset about an all-hazard approach to assessing risk to CI, which would capture the risk of a full breadth of threats, such as floods, severe weather, wildfires, earthquakes, pandemics, and industrial accidents (OECD, 2019; Pursiainen, 2009). Three papers specifically outlined the use of an all-hazard approach through the integration of human-caused and natural hazards, instead of focusing on improving the resilience of CI against one type of risk. Many Nordic and EU countries have adopted the all-hazard approach (Fekete, 2019; Pursiainen, 2018; Rogers, 2011). In addition, the EU has set out guidelines that member states should consider any risk that could occur “on average once or more every 100 years (i.e. annual probability of one percent or more) for which the consequences represent significant potential impacts, i.e. number of affected people greater than 50, economic and environmental costs above €100 million, and political and social impact considered significant or very serious” (Pursiainen, 2018, p.636).

Finally, commonly neglected risks across CI management plans are the non-physical risks such as cyber-attacks and political threats such as privatization of CI industries and deregulation (Brown et al., 2017; Cedergren et al., 2018; Fekete, 2019). Brown et al. (2017) surveyed several CI organizations across New Zealand to identify what they believed were their most significant risks. The results found that two of the top five risks identified were non-physical such as “reputation damage and regulatory change” (Brown et al., 2017, p.46). An article in the dataset examining a Swedish railway system identified that many problems associated with the response and recovery of the infrastructure are the result of the deregulation of the railway, underfunding, prioritization of efficiency and the responsibility of operation and maintenance responsibility split between public and private actors (Cedergren et al., 2018). In conclusion, the literature largely emphasizes physical threats revealing a potential research gap analyzing the impacts of non-physical threats such as cyber-attacks and political threats.

4. Types of Infrastructure

Globally, the dominant infrastructure sectors are energy, water, transport, information and technology communications (ICT), health, food supply, banking and finance, government services, safety and emergency services (OECD, 2019). The systematic review indicated that the research largely focuses on three infrastructure sectors, including electric power, transportation, and water. The following infrastructure types were the most mentioned within the dataset as critical infrastructure: power and energy (n=32); transport (n=30); water (n=29); ICT (n=18). This finding makes sense as power, transport and water are vital for the functioning of society, and in particular, power and energy are necessary to enable the functioning of most other CI sectors. Interestingly, there is minimal research and discussion around the healthcare and emergency services sectors despite their necessity for the functioning of society and particularly their vital role in crises and disasters, leaving a significant research gap around those sectors and their resilience.

Eleven articles in the dataset to focus on power systems in their research, to illustrate frameworks or case-study application of a framework or model (Bloomfield et al., 2017; Dick et al., 2019; Fang &

Sansavini, 2019; Krishnamurthy et al., 2020; Murdock et al., 2018; Nazarnia et al., 2020; Ouyang et al., 2019; Rachunok & Nateghi, 2020; Roe & Schulman, 2012; van der Merwe et al., 2020; Zimmerman et al., 2017). These articles seek to model and assess the resilience of power systems, particularly through case studies in specific regions, or to assess the interdependencies of two or three CI sectors, including power systems, to understand the overall system's vulnerabilities. The predominance of power systems is likely due to the interconnectedness of power systems. The disruption of power systems can have severe cascading effects, such as the power outage in North America in 2003, which disrupted communication systems, public transit and water distribution (Applegate & Tien, 2019). Furthermore, Dick et al. (2019) argued that resilience of electricity-related infrastructure is important to ensure public safety and reduce supply disruption, asserting that replacing and repairing ageing infrastructure is imperative due to its importance. Additionally, Krishnamurthy et al. (2020) applied a model to evaluate the resilience of a Texas electric power grid since cascading effects of power outages can cause widespread blackouts.

Articles in the dataset that focused on transportation infrastructure were highly technical and typically involved modelling the impacts of a particular threat. Several proposed technical models and frameworks seek to assess threats, identify interdependencies, and assist in decision-making during a crisis to ensure the operation and functioning of transportation infrastructure. For example, Comert et al. (2018) sought to reduce the vulnerability of intelligent traffic signals to cybersecurity attacks as the authors state that resilient transport networks are critical for resilient cities. Tonn et al. (2020) studied infrastructure resilience metrics. They applied them to a real-life transportation system: Amtrack, a passenger rail service in the United States which can then improve other transportation infrastructure systems. Additionally, transportation infrastructure is also studied alongside power infrastructure as they both play important roles in recovery and resilience during a disaster (Murdock et al., 2018).

Although water was one of the top three researched infrastructures within the dataset, there appears to be sparse research relative to power and transport since there were only five articles in the dataset that researched water infrastructure (Applegate & Tien, 2019; Johansen & Tien, 2018; Nazarnia et al., 2020; Pant et al., 2018; Zimmerman et al., 2017). Water infrastructure was also only studied alongside other types of infrastructure such as power and transportation and not studied within the dataset alone. The research focuses on modelling interdependencies between water and other infrastructure. For example, several developed highly technical frameworks to understand the vulnerability of a system of infrastructures, including water, to assess the system's resilience. For instance, Nazarnia et al. (2020) applied a framework to the water infrastructure service in Bhaktapur, Nepal, to better understand the interdependencies between water and power infrastructure disruption following an earthquake. Zimmerman et al. (2017) presented a framework that assesses recovery and interdependencies between infrastructure following an extreme weather event, focusing on three types of infrastructure: electric power, transportation, and water. Bloomfield et al. (2017) presented a tool to analyze interdependencies between infrastructures using the case study of the power and communication networks in Rome, Italy. Furthermore, de Bruijn et al. (2019) highlighted the importance of analyzing the cascading impacts of disruptions to transport and communication networks following extreme weather events due to their connection to emergency management and recovery. Most research focuses on a specific type of infrastructure instead of analyzing the cascading effects.

Several other CI sectors had limited discussion and study across the dataset, such as food production and distribution systems (n=12); healthcare (n=7), emergency services and first responders (n=3); and manufacturing (n=3). Although there were twelve articles in the dataset to include food production and distribution, no article focused on examining the food system's resilience. Mcdonald et al. (2018) is the only article across the dataset to examine the impacts of a significant disruption (worldwide pandemic) on the healthcare system and the associated economic losses and cascading impacts to other CI sectors such as emergency services. In conclusion, there is limited analysis of CI sectors outside of power, transportation, and water. In particular, significant sectors such as healthcare and emergency services receive less attention despite their vital role in crises and disasters, creating a research gap around those sectors and their resilience.

Themes among Research Objectives and Findings

The codebook provided in the previous sections was analyzed to identify major themes among research objectives and findings. This section provides an overview of the major themes within the articles in the dataset which includes:

1) Enhancing resilience (n=27);
2) Assessing resilience (n=22);
3) Case studies (n=22);
4) Frameworks (n=20); and,
5) Research gaps (n=15)

1. Enhancing Resilience

Of the 39 articles in the dataset, 27 papers present or explore frameworks, tools and technologies to enhance the resilience of critical infrastructure. The emphasis is on utilizing technology and quantitative models and frameworks to enhance resilience. There is little discussion around public policy tools such as market incentives or legislation and policies as a mechanism to enhance resilience.

There were eleven articles in the dataset that discussed specific technological innovations that seek to enhance resilience (Croope & McNeil, 2011; Curt & Tacnet, 2018; Dick et al., 2019; Dormady et al., 2019; Espada et al., 2017; Fang & Sansavini, 2019; Johansen & Tien, 2018; Murdock et al., 2018; Rød et al., 2020; Serre & Heinzlef, 2018; Wei et al., 2019). Previous reviews of tools and techniques to enhance the resilience of CI have found limited application and operation of these tools (Curt & Tacnet, 2018; Rød et al., 2020). For example, Curt & Tacnet (2018) found that technological models such as Bayesian networks, multicriteria aggregation and knowledge-based systems can be used to improve resilience. The authors found that they can overcome barriers such as a lack of operational metrics and the complex decision-making involved in disruption events. Furthermore, Rod et al. (2020) presented a standardized CI resilience management framework for CI operators and techniques for CI resilience assessment. Although the authors focus on resilience assessment techniques, they briefly conclude that it is impossible to operationalize CI resilience enhancement without measurable CI resilience assessment and quantifiable indicators. Other technological tools proposed in the literature include decision support systems, geographic information systems (GIS), stochastic programming, probabilistic multi-scale modelling, multi-regional computable general equilibrium (CGE) model, deep learning and machine vision as probable tools for enhancing CI resilience (Croope & McNeil, 2011; Dick et al., 2019; Fang & Sansavini, 2019; Johansen & Tien, 2018; Wei et al., 2019). The technological solutions targeted for enhancing CI resilience are structural actions specifically related to the physical structures or systems. However, nonstructural actions (i.e. using knowledge, practice or agreement to enhance resilience) can provide a robust, holistic approach to enhancing societal resilience (Curt & Tacnet, 2018).

Across the literature, there is an assumption that private sector stakeholders are primarily responsible for improving CI resilience since most CI is owned and operated privately (Boin & McConnell, 2007; Cutts et al., 2017; Egli et al., 2019; Ridley, 2011). For example, Labaka et al. (2016), Espada et al. (2017), and Ouyang et al. (2019) all presented technological models and tools to assist in improving the resilience of CI. The solutions indicate that resilience falls onto CI operators and managers but fails to discuss the necessary incentives the CI stakeholders need to invest in preventative risk management (Boin & McConnell, 2007). Similarly, Ridley et al. (2011) proposed that CI resilience is now a CSR phenomenon due to the widespread privatization of CI sectors globally. Van der Merwe et al. (2020) also presented novel findings that suggest a sense of coherence (i.e. how a person would perceive, cope and recover from a risk) among employees working in a CI organization may improve resilience following an extreme event. The researchers concluded that due to CI’s impact on national and global security, additional study and contributions from CSR researchers are useful in understanding how resilience can be incorporated.

There is limited support in the dataset for the responsibility of risk to be shifted onto governments and policymakers. Some frameworks and research are providing detailed direction for the burden of responsibility for each stakeholder, which mainly includes adequate training and preparation for CI operators, different levels of government, emergency responders, as well citizens, media and businesses as the means that would enhance the resilience of CI (Boin & McConnell, 2007). For example, Egli et al., (2019) emphasized the importance of collaboration with the local government since most disaster and emergency response occurs at the community level. However, most public-private partnerships occur at the federal and state level. Similarly, de Bruijn et al. (2019) emphasized the importance of stakeholder collaboration between local government, emergency responders and CI operators. Labaka et al., (2016) provided a detailed framework of resilience policies to improve the resilience of CI, which includes principles such as government preparation, public crisis response budget, societal situational awareness and first responder preparation.

Some literature indicates that legislation or market forces should not drive CI resilience, rather partnerships between the private and public sectors are the solution (Boin & McConnell, 2007; Egli et al., 2019). There is, however, minimal discussion around the incentives and motivations that would drive implementation of these solutions. Furthermore, there is no discussion around the facilitation of collaboration between stakeholders through tools such as market mechanisms or legislation. Furthermore, there is hardly any discussion around collaboration with local government despite their significant role in protecting CI (Egli et al., 2019).

There is also limited research across the dataset addressing the need for robust public policy tools to enhance resilience. However, briefly mentioned in the dataset include incentives for private sector CI (Boin & McConnell, 2007), public sector investment into CI sectors and robust government leadership through legislation of resilience and enforcement (Cutts et al., 2017). Brown et al. (2017) provided a case study of the effectiveness of CI resilience in New Zealand, where the government has implemented robust legislation requiring resilience across CI operators and demonstrated the strength of the country's policy efforts. Labaka et al. (2016) is the only article in the dataset to explicitly state that governments should establish regulations that state "minimum requirements that CIs need to ensure their safety and high reliability" (p.29). Although the literature indicates that a missing component in resilient CI is the lack of robust regulation, there is limited analysis around effective regulation and recommendation for robust regulation across the dataset (Cedergren et al., 2018; Fekete, 2019; Garschagen & Sandholz, 2018; Pursiainen, 2018). The lack of discussion around regulation is a barrier to CI resilience because many CI sectors are privately owned and operated in North America and Europe. Both regions focus more on public-private partnerships (PPPs) than direct regulation.

The literature indicated that there is hesitancy for further regulation implementing CI resilience measures. The reasons suggested include concerns that further regulation would require the internalization of costs from CI disruptions, necessitate tort liability legislation and potentially precede demands from consumers for compensation of losses following disruptions to CI services (Pursiainen, 2018). There was no other article within the dataset to discuss public policy tools surrounding CI resilience. Based on these findings, there is evidence of a research gap across the literature in the dataset surrounding the analysis of current public policy tools on CI resilience.

2. Assessing Resilience

The assessment of CI resilience is still an emerging area, typically focusing on the technical attributes of CI, and although there are several models, they are primarily theoretical with limited operative use and empirical examples (Brown et al., 2017; Pursiainen, 2018; Rød et al., 2020; Tonn et al., 2020). There were 22 articles in the dataset that included or focused on exploring the assessment of CI resilience. The articles in the dataset either focused on establishing or examining a quantitative or qualitative framework for CI resilience with limited combination between the two approaches.

Quantitative frameworks examined indicators surrounding the physical structure or performance of CI. For example, Croope & McNeil (2011) presents a framework known as the Critical Infrastructure Resilience Decision Support System (CIR-DSS), which uses indicators such as physical damage and pre- and post-event response and recovery to assess resilience. Serre & Heinzlef (2018) assessed CI resilience using three capacities: resistance capacity (analyzing the physical damages), absorption capacity (alternatives that can be used when a failure occurs) and recovery ability (the time required to restored damaged components).

Several articles identified the indicator of "service disruption" and its variations. There is a pattern in the literature indicating that this approach is becoming the predominant quantitative measurement of CI resilience as it may overcome the challenge that exists with the use of physical damages as an indicator to measure resilience. For example, Murdock et al. (2018) assessed CI resilience using the indicators "Expected Annual Damage" and "Expected Annual Disruption," and similarly, (de Bruijn et al., 2019) uses the indicator "person disruption days." Nazarnia et al., (2020) presented a novel framework using similar CI service disruption data (the number of households which experience service disruption and the duration of service disruption) to quantify CI resilience effectively. Zimmerman et al., (2017) utilized the indicator of duration of service outages, as well as recovery rates and costs of associated disruptions. Several frameworks focus on service disruption and recovery time as indicators indicating substantial overlap and redundancy across the articles in the dataset. The research also indicates limited real-life use of the frameworks and indicators presented by CI owners and operators (Kozine et al., 2018).

Additionally, several frameworks utilize qualitative indicators to examine and assess CI resilience, but there is little consistency between the research around the best qualitative indicator for resilience. The examples within the dataset include frameworks with many qualitative indicators, demonstrating that the qualitative assessment of CI resilience is very complex and likely to be context-dependent. For example, two studies assessed resilience in one or more organizations and consulted with employees to build out a list of indicators specific to their organization. Examples of indicators are provided in Table 12 (Brown et al., 2017; Tonn et al., 2020). The two lists contain the most extensive number of indicators within any other article within the dataset. These indicators did not appear in any other article in the dataset as they were created for specific organizations. This alludes to the potential conclusion that CI resilience indicators might need to be tailored to specific industries or even specific organizations and therefore could be limited for generalization across sectors. van der Merwe et al., (2020) successfully utilized a novel indicator for assessing CI resilience – sense of coherence (SOC) – and found that in a CI organization, when there was a higher SOC among employees, there was a positive correlation with resilient outcomes following a disruption. Similarly, Robert et al. (2015) presented a framework for assessing the resilience of CI using coherence analysis including three pillars: acceptance, planning and anticipation and their associated criteria, which allows for CI organizations to identify gaps and prioritize the actions which would improve CI resilience. Across the dataset, there was only one framework that combined quantitative and qualitative indicators for a more advanced, holistic understanding and assessment of CI resilience (Croope & McNeil, 2011).

Although the research includes some empirical application of qualitative CI resilience assessment in various organizations, there is no academic or real-life consensus surrounding the most effective method for assessing CI resilience which hinders its practical application and execution. There remains a need for further research which explores the limitations of a standardized CIR management process in the industry and an analysis of the industry's current state in terms of its perspective and practice of CI resilience assessment.

Table 12: Example indicators for organizational resilience (Brown et al., 2017; Tonn et al., 2020)

Staff engagement
Effective partnerships
Stress testing plans
Collecting weather data
Communication systems – staff
Training drills
Insurance coverage
Operational funding for resilience initiatives
Capital availability for resilient infrastructure

3. Case Studies

Out of the 39 articles in the dataset, 22 focused on or included a case study. This section describes the three following parameters of the case studies: geographic location, hazard, and CI sector.

Geographically, the case studies focused almost exclusively on the Global North and, in particular, North America. Outside of the Global North, only one developing country indicated a lack of geographic variability within the case studies in this data. Eleven case study locations were in North America (Croope & McNeil, 2011; de Bruijn et al., 2019; Dick et al., 2019; Krishnamurthy et al., 2020; Murdock et al., 2018; Rachunok & Nateghi, 2020; Ridley, 2011; Robert et al., 2015; Roe & Schulman, 2012; Tonn et al., 2020; Zimmerman et al., 2017). Of those eleven articles, nine are in the United States. The remaining three case studies are in Canada (Murdock et al., 2018; Robert et al., 2015; Zimmerman et al., 2017). The remaining study locations include Australia (Espada et al., 2017), Britain (Ridley, 2011), Germany (Serre & Heinzlef, 2018), Italy (Kozine et al., 2018), Nepal (Nazarnia et al., 2020), New Zealand (Brown et al., 2017), Portugal (Rød et al., 2020), South Africa (van der Merwe et al., 2020) and Sweden (Cedergren et al., 2018). Two articles out of the 22 did not have a stated study location and there was no indication of any regional or national application (Dormady et al., 2019; Labaka et al., 2016). More specifically, Dormady et al., (2019) presented four mathematical case studies to apply their production theory and demonstrate a resilience cost-benefit analysis and Labaka et al., (2016) demonstratec their resilience framework in two case studies using the examples of a nuclear power plant and water distribution company.

In addition to geographic diversity, case studies also varied in terms of the hazard they analyzed. Many case studies did not focus on one specific hazard. Instead, they demonstrated the resilience of a system to various hazards, which aligns with the literature's recommendation to focus on an all-hazard approach. Within the case studies that did focus on a specific hazard, they were almost exclusively physical hazards, and in particular, they focused on flooding, earthquakes and hurricanes. Overall, the case studies did not focus on non-physical hazards, indicating a significant research gap around an empirical analysis of non-physical threats to CI resilience. The most commonly studied hazard in case studies across the dataset was flooding, included in five articles out of 22 (Croope & McNeil, 2011; de Bruijn et al., 2019; Murdock et al., 2018; Pant et al., 2018; Serre & Heinzlef, 2018). Other hazards studied in the case studies include earthquakes and hurricanes (Dormady et al., 2019; Rachunok & Nateghi, 2020), falling trees (Dick et al., 2019), and shortage of drinking water (Robert et al., 2015). Eleven articles out of the 22 in the dataset did not state a specific hazard in their case studies and typically stated that the case study was analyzing any disruptive event that would occur to the CI or did not state anything related to a hazard (Brown et al., 2017; Cedergren et al., 2018; Fang & Sansavini, 2019; Kozine et al., 2018; Labaka et al., 2016; Nazarnia et al., 2020; Ridley, 2011; Rød et al., 2020; Tonn et al., 2020; van der Merwe et al., 2020; Zimmerman et al., 2017).

Finally, the case studies varied in terms of the CI sector, which they analyzed. In alignment with the previous section, the most researched CI sector within the case studies was power, transportation and water. Similar to the previous section, the results indicate much less focus on CI sectors outside of these three, presenting a significant research gap. The most observed CI sector in the case studies across the dataset was the power sector; power was studied in nine case studies (Brown et al., 2017; Dick et al., 2019; Fang & Sansavini, 2019; Krishnamurthy et al., 2020; Nazarnia et al., 2020; Rachunok & Nateghi, 2020; Roe & Schulman, 2012; van der Merwe et al., 2020; Zimmerman et al., 2017). Second, eight of the 22 articles focused on transportation (Brown et al., 2017; Cedergren et al., 2018; Croope & McNeil, 2011; Murdock et al., 2018; Ridley, 2011; Serre & Heinzlef, 2018; Tonn et al., 2020; Zimmerman et al., 2017).

The other infrastructure studied in the case studies across the dataset are water (n=6) (Brown et al., 2017; Johansen & Tien, 2018; Labaka et al., 2016; Nazarnia et al., 2020; Rød et al., 2020; Zimmerman et al., 2017), telecommunications (n=2) (Brown et al., 2017; Ridley, 2011), and nuclear power (n=1) (Labaka et al., 2016). Four articles in the dataset did not specify any specific CI sectors in their case study (de Bruijn et al., 2019; Espada et al., 2017; Pant et al., 2018; Robert et al., 2015). Furthermore, two case studies did not focus on any CI sector. Instead, they conducted case studies around the economic resilience of a private organization (Dormady et al., 2019) and how public-private partnerships contribute to CI resilience (Kozine et al., 2018). Most case studies applied a framework developed to demonstrate the assessment or enhancement of the resilience of a particular infrastructure sector(s) to either a specific hazard or various disruptive events.

In summary, the case studies conducted within this dataset focused almost entirely on the Global North and specifically in North America, with only one reference of a case study outside of the Global North (Nepal). The case studies also focused on assessing or enhancing resilience to physical hazards, particularly flooding, with no reference to non-physical hazards. Finally, the case studies primarily focused on analyzing the resilience of power, transportation and water sectors with little attention to sectors outside those three.

4. Frameworks

Twenty articles in the dataset presented or developed novel frameworks in their research. A framework, in this context, refers to a network of interlinked concepts where each play an integral role to provide an understanding of a phenomena (Jabareen, 2009). The frameworks varied based on whether they were quantitative or qualitative, whether they were empirical or theoretical, and the intended users of the framework.

The articles in the dataset that presented frameworks were predominately quantitative, which aligns with previous findings reported in this chapter that CI resilience research remains highly technical. Furthermore, the case studies were predominately empirical, and within the research, they would present a framework and then demonstrate the application of the framework through a case study. Finally, the stated intended users of the framework were primarily for government leaders and policymakers, which conflict with the dominance of highly technical and quantitative frameworks. It was unclear how policymakers would interpret and apply technical frameworks. Additionally, there was little information regarding how the authors of these frameworks intended this information to be disseminated to their intended users.

Out of the 20 articles, 13 presented quantitative frameworks (Applegate & Tien, 2019; Dormady et al., 2019; Espada et al., 2017; Fang & Sansavini, 2019; Johansen & Tien, 2018; Krishnamurthy et al., 2020; McDonald et al., 2018; Nazarnia et al., 2020; Pant et al., 2018; Rachunok & Nateghi, 2020; Tonn et al., 2020; Wei et al., 2020; Zimmerman et al., 2017). Six articles presented qualitative frameworks (Clark et al., 2018; Egli et al., 2019; Fekete, 2019; Kozine et al., 2018; Labaka et al., 2016; Rød et al., 2020). Only one framework combined qualitative and quantitative metrics and the research objective was to build a decision-support system to assess and improve CI resilience following a disaster (Croope & McNeil, 2011).

The frameworks were predominantly empirical (n=13), presented by the authors and then demonstrated through an applied case study (Applegate & Tien, 2019; Espada et al., 2017; Fang & Sansavini, 2019; Johansen & Tien, 2018; Kozine et al., 2018; Krishnamurthy et al., 2020; Labaka et al., 2016; Nazarnia et al., 2020; Pant et al., 2018; Rachunok & Nateghi, 2020; Tonn et al., 2020; Wei et al., 2020; Zimmerman et al., 2017). In contrast, seven articles presented purely theoretical frameworks and did not include any empirical application (Clark et al., 2018; Dormady et al., 2019; Egli et al., 2019; Fekete, 2019; McDonald et al., 2018; Pant et al., 2018; Rød et al., 2020).

Another essential factor concerning the frameworks presented across the dataset is the stated intended users of the framework. Eight articles in the dataset outlined the users of their frameworks as government leaders and policymakers (Clark et al., 2018; Croope & McNeil, 2011; Egli et al., 2019; Espada et al., 2017; McDonald et al., 2018; Nazarnia et al., 2020; Pant et al., 2018; Wei et al., 2020). Five articles that presented frameworks outlined the users as CI owners and operators (Dormady et al., 2019; Fang & Sansavini, 2019; Labaka et al., 2016; Rød et al., 2020; Tonn et al., 2020). Five articles did not state who the users of their framework would be (Fekete, 2019; Johansen & Tien, 2018; Kozine et al., 2018; Krishnamurthy et al., 2020; Rachunok & Nateghi, 2020). Finally, one article stated that there were multiple users of their framework, which included "decision-makers, planners and [CI] operators" (Zimmerman et al., 2017, p.1).

Based on these findings, there is more of a focus on quantitative frameworks than qualitative frameworks, and indeed, limited frameworks combine quantitative and qualitative metrics. Furthermore, there is preliminary research for frameworks that many actors can use but only one framework stated their intended users were multiple stakeholders. Finally, there was little discussion surrounding the dissemination of frameworks for real-life usage by any stakeholders or how technical frameworks could adapt for usage by government leaders and policymakers.

5. Research Gaps

Many research gaps were presented in the articles across the dataset, but they were predominately more quantitative research gaps than qualitative. Most research gaps listed in the articles across the dataset are related to further advancing knowledge around the assessment of vulnerabilities, risks, CI resilience and the application of frameworks. For example, Garschagen & Sandholz (2018) highlighted the significant research gaps in the literature surrounding the assessment of social vulnerability and the connection to CI failures. Most research on vulnerability assessments refers to the direct impacts of an environmental disaster on households or individuals. However, there is little research around understanding how CI disruption or failure would have various societal impacts, such as the secondary impacts of water or electric power failure (Garschagen & Sandholz, 2018).

Furthermore, Pant et al., (2018) stated that a significant research gap in the literature is the lack of research conducted to quantify the flood risk on CI, particularly since flooding is the most significant risk in many areas of the world and will increase in intensity and frequency under every climate change scenario (UNEP, 2020). In addition, there is also a significant research gap for other non-physical hazards such as cyber-attacks and political threats. Furthermore, there remains a significant research gap that can also utilize household disruption service data and patterns and the status of end-users of CI services to characterize infrastructure resilience in other regions (Nazarnia et al., 2020). Similarly, there is insufficient research that quantifies and represents infrastructure network interdependencies which is critical for understanding the cascading effects of CI failure (Pant et al., 2018).

The qualitative research gaps include the further exploration of policies that reduce CI resilience, the overlap of CI resilience with other fields of research such as disaster risk management and corporate social responsibility, and the exploration of the application of frameworks for the assessment of CI resilience. For example, Cedergren et al., (2018) briefly explored the connection between deregulation and underfunding on the Swedish railway system and suggests the further exploration of the role privatization and deregulation have played on impacting the resilience of CI and their recovery capabilities. Authors in the dataset have presented essential research gaps related to CI literature's lack of connection and overlap with other fields, particularly disaster risk management and corporate social responsibility. Fekete (2019) stated that the bridges between disaster risk management and CI literature are incredibly understudied despite the vital connection, mainly as flood risk is one of the most significant global risks. The subsequent damage to infrastructure presents paramount costly and lethal risks.

Furthermore, Ridley (2011) pointed out that since CI resilience is studied primarily in technical contexts (i.e. engineering), it limits the knowledge and tools that can be utilized and adapted from other fields to assist in problem-solving. Similarly, Clark et al., (2018) suggested that leveraging business knowledge around resilient supply chains can facilitate and strengthen CI resilience since many companies have developed resilience strategies and plan to ensure they can provide their products and services. Several authors in the dataset state that there are several frameworks in the literature, but there is limited standardization in the field of CI resilience assessment, and the application of frameworks in CI organizations has not been adequatly explored (Kozine et al., 2018; Labaka et al., 2016; van der Merwe et al., 2020). Finally, adequate research has not been conducted to sufficiently explore the connection between CI resilience and infrastructure interdependencies despite their essential and intricate connection (Zimmerman et al., 2017).

Chapter 5: Discussion

The objective of this study was to contribute to the existing knowledge of critical infrastructure resilience by systematically reviewing scholarly literature, analyzing major and minor themes and identifying future research direction. This chapter answers the research questions stated in Chapter 1, draws connections between Chapters 2 and 4 and provides future research directions for critical infrastructure resilience.

Lack of Overlap with Other Research Fields

Aside from natural hazards and flooding, there remains limited research of CI in various research fields outside of engineering. Engineering continues to be the dominant field for most CI resilience research. Although there is some crossover in the social sciences field, the limited research in other fields impedes the development of knowledge and tools that can be utilized and adapted from other fields to assist in problem-solving. CI resilience research in the engineering field means that the problems and solutions are framed in a technical context and are likely why many solutions for enhancing resilience are technological innovations. CI resilience research is emerging in the fields of business and economics as well as disaster management. It remains understudied, which means that the extant perspectives, knowledge and tools of CI resilience are in the engineering field and need to be diversified through the perspectives and knowledge of other research fields and has limited the application of the concept in real-life. As noted in Ridley (2011), there is a need for more CI resilience research in the business and economics to ensure that private sector actors who own and operate critical infrastructure understand the necessity for resilience as how to operationalize the concept.

In addition, the fields of ecology, natural hazards and disaster management have been studying resilience to physical threats for several decades and have much knowledge to offer to develop the concept of CI resilience further.

A Robust Definition of CI Resilience

Chapter 2 introduced the various definitions of resilience and the evolution of the term academically from its conception. Resilience when applied to CI largely reflected concepts and definitions developed within the fields of engineering and physics. However, as the literature has concluded, there are several limitations with this understanding of resilience as it is a narrow definitin more closely related to physical infrastructure and is not always ideal for societies to return to a pre-disturbance state after a stress or disaster has occurred, because that pre-disturbance state which was impacted has indicated some degree of vulnerability. In the context of societal resilience, many times it is more effective to change to a new state which can be more resilient to future disasters. Some literature indicates a more advanced understanding of CI resilience drawing from ecology, psychology, disaster management and complex adaptive systems. In particular, the conceptualization of resilience is the ability to learn from stresses and disturbances to better prepare for unforeseen events in the future (Martin-Breen & Anderies, 2011). Unfortunately. as Chapter 4 indicates, the widespread use of the definition of CI resilience without an established definition has made it difficult to operationalize. There was little consistency between the definitions among the articles in the dataset, which substantiates the claim that there is no established term. Two conclusions arose from the results regarding a more robust definition of CI resilience. The first is that CI resilience incorporates four components:

1. Planning and preparation: a resilient system cannot always prevent a hazard or disruption from occurring but plans and prepares for such events to occur;

2. Reduction of impacts: a resilient system should focus on reducing the impacts of a hazard or disruption so that it does not become disastrous;

3. Minimal recovery times: a resilient system is capable of reducing the disruption to physical infrastructure services to minimal recovery times and;

4. Learning and evolution: a resilient system learns from previous hazards and disruptions and evolves to better cope with disturbances in the future.

Second, CI resilience should explicitly focus on the vital services the infrastructure provides and the physical infrastructure, since their primary purpose is to deliver a vital service to society. The increased focus on the services infrastructure provides is an evolution from the historic narrow definition which is more closely related to the physical infrastructures’ resilience. Furthermore, a focus on the service the infrastructure provides ensures that when a stress or disaster occurs, the primary focus is on restoring vital services to society which are required to prevent significant adverse impacts to the well-being of citizens and adverse effects to the economy.

Risks to CI

Chapter 2 identified several threats to CI, both physical and non-physical, including terrorism, natural hazards and climate change, ageing infrastructure, cyber-attacks and political threats. The results indicate an over-emphasis on the analysis of physical threats to CI and the absence of discussion surrounding the non-physical threats, such as regulatory change, deregulation and privatization of industries, underfunding and prioritization of efficiency to CI. The results indicate not only a lack of research and analysis on the risk non-physical threats pose to CI but also a lack of acknowledgement that non-physical threats exist and that they do influence the resilience of CI. The consequence of this is not having a comprehensive understanding of the actual vulnerability of CI. Without a good understanding of the risks to CI, it is much more challenging to improve the resilience of CI effectively. Given the large global landscape of threats to CI, many have the potential to not only cause a disruption to society but can lead to a nationwide breakdown of CI networks which could render the country’s economy and society non-functional. For example, the earthquake in Japan which caused a subsequent tsunami and caused the loss of functioning of a nuclear power plant which led to large-scale radioactive contamination in the country (Osei-Kyei et al., 2021). Given this conclusion, the results from this researh indicate a lack of understanding of the full landscape of threats to CI including a prevailing threat of cyber-attacks in the current digital age.

As indicated in Chapter 4, only three papers noted cyber-threats as a risk to CI despite the increasing dependence of CI sectors on digital control systems and networking resources and the more frequent real-life scenarios where cyber-attacks threaten national security such as the increasing rate of cyber-attacks on government agencies, telecommunication, cloud-based document storage systems and even emergency responder services (U.S. Department of Homeland Security, 2021). Without a robust understanding of how cyber-attacks pose a threat to CI resilience, many countries’ national security and safety is at risk since cyber-attacks can not only compromise data and information, which poses a more major security threat but can also severely disrupt critical services and create cascading impacts that have a far-reaching effect globally. One such example was seen in 2017 when Wannacry ransomware spread and infected more than 200,000 computers in 150 countries. It impacted many commercial and government institutions including FedEx, Deutche Bahn, Megafon, Telefonica, the Russian Central Bank and the National Health Service in the United Kingdom (OECD, 2019). Therefore, a substantial research gap persists on the non-physical threats pose to CI and their resilience.

Furthermore, a lack of understanding of how political landscapes can influence CI resilience will further hinder the developments required to improve resilience. As discussed in Chapter 2, widespread privatization and market liberalization globally have led to institutional fragmentation between CI sectors. Fiscal austerity has left many CI sectors unequipped to prioritize resilience financially. Still there were only two research papers in the dataset which mentioned how these factors could influence resilience. Exclusively privately-owned CI sectors operating under the guise of free-market principles cannot protect vital services. Publicly-owned CI sectors operating under fiscal austerity are also not equipped to the protection of vital services. Without a deeper understanding of how these threats pose a risk to CI, resilience is not possible (de Bruijne & van Eeten, 2007).

CI Resilience and Natural Hazards

Although there is some indication that flooding is the primary focus among the research in this dataset in terms of the interaction between CI resilience and natural hazards, overall, there is limited research on the impact of natural hazards on critical infrastructure resilience. The results indicated that there were only three papers papers published in natural hazards' focused journals and six articles which focused specifcially on flooding. The articles in the dataset that focus on flooding are high-level methodologies and frameworks to assess CI resilience to flood or a flood resilience assessment of a particular community. Although there appears to be some understanding in how vulnerability and resilience of CI to flooding can be measured, it is apparent it is not thoroughly researched in the literature. There has been minimal application of these methods to understand how vulnerable or resilient CI globally is to flooding. Furthermore, only one article acknowledged the necessity to integrate the concepts of CI resilience and natural hazards, which all concludes that the connection between the two topics is understudied.

As discussed in Chapter 2, natural disasters and extreme weather, specifically flooding, pose a significant threat to CI globally. A limited understanding academically of the degree to which these risks pose a threat and how to enhance resilience to natural disasters, global communities remain highly vulnerable. As climate change increases the frequency and intensity of natural hazards and extreme weather, research must focus on examining the connection between CI resilience and natural hazards to improve the overall resilience of society.

Emphasis on Technical Solutions

Across the literature, there is still an emphasis on developing and implementing technological solutions to enhance the resilience of CI. The emphasis on technology to improve resilience focuses almost exclusively on the physical structures and systems. It is not capable of addressing the non-structural actions that are also necessary to improve CI resilience effectively. As discussed in Chapter 2, the origins of CI protection emerged in the engineering field, where solutions were discussed exclusively in technological contexts, and technological solutions typically focus on anticipating risk and protecting the physical structures. Although many scholars have long criticized the over-emphasis on technological solutions, the results indicate the literature has not evolved much over the years. Although the literature indicates that technical solutions (examples include retrofitting buildings to withstand natural disasters ro vaccines to prevent viral disease spread) can prevent harm in society, the overemphasis has dominated political agendas and shifted resources away from non-technical solutions (examples include regulatory changes or social networks). Both technical and non-technical solutions are required and can work in parallel to ensure a holistic approach to resilience (OECD, 2019).

There is limited research within the dataset that explores non-technical solutions. Examples include the development and implementation of stricter regulation and, along with that, more consultation within local communities between local government, households and businesses to create contingency planning and business continuity planning to facilitate “organic” community responses to disruptions or disasters (Boin & McConnell, 2007; Pursiainen, 2018).

Responsibility for Private Sector to Improve Resilience

Chapter 2 puts forward that the critical principle for effective CI resilience is robust public-private partnerships and collaboration. Since many CIs are privately owned and managed, communication protocols and information-sharing platforms that connect private organizations and public institutions are vital to enhancing CI resilience. As many of the solutions proposed to enhance resilience are technological in nature, there is limited research surrounding how to mobilize the private sector to prioritize and take action on CI resilience through either more robust public-private partnerships, incentives or regulatory requirements. A significant component for improving the resilience of CI is more robust regulation (Pursiainen, 2018). However, CI resilience research does not adequately analyze current public policy tools intended to improve resilience. It does not recommend any substantial regulatory changes to ensure safety and reliability of CI systems or services.

The literature indicates that the exploration of regulatory solutions for CI resilience has not occurred primarily due to the hostility by the private sector towards regulatory change. A lack of regulation typically allows the private sector to externalize the costs of risks to CI and prevent tort liability of compensating losses from disrupted services (Pursiainen, 2018). Public-private partnerships have been proposed to ensure resilience when the government is legally responsible for CI despite the reality that CI is primarily owned and operated by the private sector, which was explored within the research but with little criticism. As a result of the limited criticism, political agendas will continue to rely on partnerships between the public and private sectors without exploring alternative options and assessing their efficacy. Other such solutions include establishing clear delineations of roles and responsibilities between governments and the private sector and stricter regulation for CI sectors that are privately owned and operated in place of self-regulation (Pursiainen, 2018).

Additionally, the solutions proposed in the literature are almost all intended for use by CI owners and operators, which implicitly shifts the responsibility to enhance CI resilience to that particular stakeholder. As identified in the literature, three other stakeholders are involved with ensuring resilience and the emphasis on technical solutions can exclude the other stakeholders, creating a barrier to operationalizing the concept in real-life. As discussed in Chapter 2, the limited perspective on the solutions for CI resilience has limited the understanding of the problem and created a significant barrier to holistic solutions. Therefore the concept requires a much broader understanding of the solutions outside of the purely technical contexts.

Uncertainty Assessing CI Resilience

Although many articles in the dataset focus on the development or application of frameworks to assess CI resilience, there is still limited consesus as to the best methods for the assessment of resilience or real-life application of standardized frameworks. Although much of the research focuses on developing a practical methodology for assessing resilience, there is inadequate research to assess current industry practices. Across the dataset, no research provides insight as to whether any CI organizations are assessing resilience, what methodology or indicators are used to assess resilience and whether the assessment of resilience has mobilized CI organizations or industries to improve resilience. These findings indicate a potential lack of communication between the scholars researching CI resilience and the owners and operators of CI. Suppose there is no coordination between the academic community and the operators of CI sectors, then the research conducted by the academic community is limited without the full breadth of knowledge of what is occuring on the ground within CI sectors. Additionally, there will also be limited implications of research findings because the two stakeholders are not communicating.

Furthermore, the significant overlap in the literature surrounding the most appropriate indicator for assessing resilience, which appears to be analyzing disruption data (e.g. the number of people who experienced service disruption and the duration of service disruption), indicates some degree of consensus in the academic community. This finding can mobilize more operationalization of resilience assessment in CI industries as well as work as the building block for a standardized CI resilient assessment tool or methodology. Future research could analyze how CI sectors assess resilience in practice and utilize research findings to apply these indicators in real-life scenarios. Analyzing indicators in practice would provide useful insight as to how to accurately assess resilience as it could capture cascading effects not present in conceptual service disruption analysis

Chapter 6: Conclusion and Future Research Directions

Communities rely on critical infrastructure (CI) to ensure the provision of critical public services, economic growth, and social development. Globally, the dominant sectors are energy, water, transport, information and communication technology, health, food supply, banking and finance, government services, safety and emergency services. Major and minor events can have significant impacts on critical infrastructure, which can cause extreme harm to the well-being of society. Since the late 1990s, countries have been designing and implementing public policies and strategies to protect CI from various threats effectively. Initially, policies were focused on the physical protection of CI to physical threats such as terrorism due to events such as the 9/11 terrorist attacks in the United States and 2004 Madrid and 2005 London terrorist attacks but have quickly evolved to reflect the evolving and unpredictable global landscape of threats such natural disasters, ageing infrastructure, cyber-attacks and many more.

Furthermore, globally widespread market liberalization and privatization policies, particularly in North American and Europe, have led to the transfer of ownership and operation of CI from the government to the private sector. Alongside this transition, there has also been a trend of deregulation of several industries and fiscal austerity, leaving many CI systems self-regulated and underfunded (Curt & Tacnet, 2018; Murray & Grubesic, 2012; Pursiainen, 2018). Furthermore, globalization has resulted in an unprecedented level of interconnectedness between countries CI leaving no country immune to the impacts of failure or disruption to their neighbour countries' infrastructure (OECD, 2019; Pursiainen, 2018).

Scholars have noted that the adoption of "critical infrastructure resilience" is necessary to ensure the safety and well-being of global communities in light of the evolving landscape of threats, including political threats and the intricate interconnectedness of global infrastructure. Furthermore, the Organization for Economic, Co-operation and Development (OECD) has established the need for governments to adopt resilience-based approaches as part of their national strategies to ensure the service continuity of critical infrastructures, but the state of academic knowledge around the concept has not been well-established. The concept has emerged in scholarly literature relatively recently. It shows promising signs of interest by researchers, but some of the most fundamental questions around the concept are still not widely understood, such as: What does critical infrastructure mean? How is it assessed?; How can governments, policy leaders, practitioners and CI owners and operators enhance CI resilience?. Furthermore, different research fields have adopted the concept of resilience and generated their definitions to ensure they relevancy of the concept to address their specific class of problems. The lack of development of critical infrastructure resilience has presented limitations in the application and operationalization in real-life.

For these reasons, this research sought to fill the research gap around establishing current knowledge of CI resilience among the literature and address several fundamental questions about the concept to ensure a consistent understanding of the concept and the literature through systematic review methodology. I chose a systematic review as they are regarded as the most effective means to synthesize information from multiple research sources. They follow a structured sequence of steps, including planning the review, searching for literature, applying inclusion and exclusion criteria to select the final list of papers, extracting data and analysis and synthesis. By following a standard methodology, they seek to be transparent and reproducible. Furthermore, through their synthesis of many sources of information, the results emerging from systematic reviews are capable of informing essential processes of decision-making, research and policy. This research utilized an adapted version of the PRISMA protocol for systematic reviews for a qualitative review.

For the methods utilized for synthesis and analysis, the researcher reviewed the data and conducted both a descriptive and thematic analysis. The descriptive analysis clarified the main characteristics in the dataset, in this case, the publication date, study location, research field and journal type, and research methodology. The descriptive analysis provided valuable insights as to the trends across CI resilience research. In addition, the research employed the six phases of thematic analysis as outlined in Braun & Clarke (2006), which includes reading the data, generating codes, searching for themes, defining themes and producing the report. This process organizes data for the research to identify patterns and key themes across research objectives and findings to report the state of knowledge in the field of study and to inform future research agendas.

There are several weaknesses of systematic reviews, such as the degree of methodological rigour used when conducting the study. There are potentially some misleading or biased conclusions. To address this limitation, the research closely followed the PRISMA checklist to best reduce bias by clearly defining and explaining each step in the methodological process to improve the transparency of the review and decrease bias. Another limitation is that systematic reviews for qualitative research with strict guidelines have limited the scope of reviews and compromised data analysis and quality of results. To address this limitation, the researcher incorporated information and findings from grey documents, such as policy documents, legislation and research reports, to offer additional insights in the research findings and gaps.

The following research questions were developed to guide the study:

1. How is CI resilience conceptualized in the scholarly literature?
2. What is the current state of knowledge and extant research findings of CI resilience?
3. What are the necessary future research directions to further advance knowledge of CI resilience?

Several conclusions drawn from the results, to answer the guiding research questions which are described in detail below.

1. How is CI resilience conceptualized in the scholarly literature?

CI resilience has only been explored and studied in the last decade withinacademic research, but there has not been enough interest by academic scholars to thoroughly and robustly conceptualize the concept. In addition, the concept has predominately been conceptualized in the context of the Global North, based on the journals reviewed, which indicates more narrow perspectives and understandings of the concept which potentially limits the application of the concept globally. Furthermore, CI resilience is conceptualized predominately in technical fields such as engineering and physics. Still, the research results demonstrate some interdisciplinary perspectives of the concept with research conducted in disaster management, human geography, political sciences, business and economics. The research results indicate that the concept will continue to be studied across various research disciplines providing a more holistic understanding of CI resilience.

2. What is the current state of knowledge and extant research findings of CI resilience?

The understanding of the term CI resilience continues to be more closely related to its origins in the engineering and physics fields. The definitions commonly used among current research emphasize the protection and minimization of impacts on the physical structures that do not capture CI's complexity, which requires a more robust definition. The definition should more closely reflect the perspectives of societal resilience, which would focus on minimizing social and economic impacts and seek to improve the system(s) ability to cope with future unanticipated events. Similarly, the focus of CI resilience research is on technical resilience. At the same time, the literature indicates that societal resilience is better equipped to reduce societal impacts from the disruption of CI from crises or disasters.

Furthermore, the literature indicates an over-emphasis on examining physical risks to CI, which has left a substantial research gap analyzing the impacts of non-physical hazards (e.g. cyber-attacks and political threats, such as deregulation and privatization) on the resilience of CI. The CI resilience research focuses primarily on energy, transport and water infrastructure, which has left several vital sectors neglected in the research. CI sectors such as food production and distribution, healthcare, emergency services and first responders, and manufacturing which play an integral role in the functioning of society, have almost entirely been left out of the current CI resilience research.

Finally, the CI resilience research primarily focused on enhancing resilience, assessing resilience, applying case studies, or developing frameworks for CI resilience. Research results indicated an over-emphasis on technical solutions to enhance resilience and suggested a limited understanding and analysis of how public policy tools can work to enhance CI resilience. Similarly, many frameworks developed in the research are primarily quantitative and technical, intended to be used by owners and operators of CI. There is limited use of qualitative frameworks for enhancing or assessing resilience that could be used by policymakers or government leaders for non-technical solutions. Additionally, much of the research in the dataset seeks to understand how to assess CI resilience best. Although there is some indication of a most effective method for assessing resilience, in this case, it uses the indicator “service disruption days”, the results further indicate a limited usage of consistent indicators in real-life CI sectors.

3. What are the necessary future research directions to further advance knowledge of CI resilience?

Based on the research findings provided in this review, the following future research directions are provided in detail below.

Additional Development of CI Resilience in Social Sciences Research Disciplines

As identified in the research results, the concept of CI resilience remains understudied in fields outside of engineering which, as criticized by several scholars has limited the understanding of the problems surrounding CI, barriers and challenges and the holistic solutions for effective risk management.Without a robust understanding of the concept in socio-political and behavioural science contexts, the problems and solutions surrounding CI resilience will remain highly technical and likely result in limited operationalization in political agendas, particularly at the local level. For this reason, future research surrounding CI resilience in various social sciences research disciplines is highly recommended to improve the academic understanding of the concept outside of its technical contexts and enable the integration into political agendas and governance tools. Future research could work closely with the OECD as they publish regular research reports surrounding the socio-political dimensions of CI resilience globally (OECD, 2019).

More Geographically Diverse CI Research

The research results indicate a lack of CI resilience research outside of the Global North which substantially limits the perspectives and knowledge on the concept. In particular, based on the dataset in this research, developing countries were almost entirely excluded which hinders the ability for CI resilience to apply in those countries. Investment in the infrastructure of developing countries is an important goal of many international agreements, including the Paris Agreement, which seeks to mitigate global climate change and adapt to its adverse impacts (OECD, 2021). If there is to be accelerated investment, development and retrofitting of infrastructure in these countries it is vital to have the knowledge for how exactly the infrastructure needs to be developed to ensure effective resilience to a wide range of risks in those countries. For this reason, future research surrounding CI resilience should be more geographically diverse and perhaps focus more specifically on developing countries as they appear to be almost entirely neglected from the data.

Increased Focus on Societal Resilience

The literature indicates that societal resilience is needed to respond during CI disruptions and disasters. This is, however, a limited focus on societal resilience in CI resilience research. Researchers in the disaster management discipline have developed a solid base of evidence to support the role of social cohesion in understanding how well a community recovers following a disaster. For example, researchers observed a more efficient recovery in low-income communities following severe flooding due to Hurricane Katrina compared to the richer neighbourhoods in New Orleans, which were less damaged and did not recover as efficiently. The factor impacting recovery was determined to be the high social capital (Aldrich & Meyer, 2015). Therefore, future CI resilience research should focus more on assessing and enhancing societal resilience to understand how social capital and networks can reduce the social and economic losses and impacts from disruptions to CI.

Climate Change, Natural Hazards and Flooding

Finally, as climate change continues to pose a severe and significant threat to many societies and their critical infrastructure, there is a need for future research to focus on the intersection between climate change, natural hazards, floods and critical infrastructure resilience. Future research should seek to understand the degree to which critical infrastructure is at risk due to climate change, in the form of extreme weather, natural hazards and flooding, and what measures, tools and technologies must be put into place to ensure the resilience of CI. The OECD has identified climate change and the associated risks such as flooding and sea-level rise as significant current and future risks to critical infrastructure systems globally (OECD, 2019). Climate change poses a unique threat as it causes increasingly frequent and intense disaster events that cannot be predicted by historical data. Therefore, climate change requires designing, adapting and retrofitting infrastructure which is capable of withstanding unprecedented events. Research in this area is needed to provide insights and guidance to inform effective and efficient investment to enable resilient critical infrastructure.

Additional Research Analyzing Non-physical Hazards

Non-physical hazards such as cyber-attacks and political threats pose a significant threat to CI resilience. The results indicate limited research analyzing the risk that non-physical hazards pose to CI, which are significant shock events that can disrupt CI's functioning and result in large social or economic impacts. In particular, the OECD identifies digital threats, like cyber-attacks, as significant threats to CI resilience as sophisticated technology can allow for digital terrorism to impact transportation infrastructure, chemical and nuclear plants and even waste systems. The findings from the OECD indicate necessary future research needs to analyze the threat of non-physical hazards to CI resilience (OECD, 2019). In addition, the global risk landscape is rapidly evolving, and there is a need for an in-depth understanding of the various risks by exploring the efficacy of an all-hazards approach to improving resilience to capture the wide portfolio of risks threatening CI effectively.

Diversifying CI Industry Research

Several CI industries are severely understudied and require further study in the future. The limited understanding of the degree to which sectors are resilient and how they can improve resilience compromises broader resilience of CI industries such as food production and distribution, healthcare, emergency services and essential manufacturing should focus on future CI research to understand their current degree of resilience in various regions and communities globally. This research is required to inform policies and practices to improve overall resilience. For example, the most recent global pandemic has brought to light the need for global health systems to assess their resilience when impacted by a highly contagious virus as many hospitals reported overcrowding, understaffing and an undersupply of personal protective equipment (Deloitte, 2020).

Examining Empirical Public Policy Tools

Future research surrounding the topics of CI resilience should conduct an in-depth analysis of the practical public policy tools currently in place aimed at enhancing CI resilience. The objective is to understand what public policy tools are in place, their efficacy, and which public policy tools are required to improve overall CI resilience better. The OECD indicates that stringent regulations such as inspections, performance assessments, mandatory business continuity plans and fines, or other penalties, for non-compliance with resilience requirements are underutilized in many OECD countries. An academic analysis of the various regulatory and policy tools for CI resilience and their effectiveness can permeate the public sector to pave the way for the adoption of more stringent measures to enhance CI resilience.

Critical Infrastructure Resilience and Systematic Reviews

Finally, CI resilience is a concept which still requires substantial academic development to establish a fundamental understanding. Although this review provided some answers to fundamental questions, there are still several questions left which require an answer. For example, which public policy tools are discussed across literature and grey documents to address CI resilience? Furthermore, there are several limitations to this review, including potential bias and some limitations to the data included in the review. Additional reviews could potentially addres the bias of this review since systematic reviews follow rigorous guidelines for its methodology, and can be easily compared and contrasted for that reason. Since CI resilience has only emerged in the academic literature in the last decade or so, there is a benefit to incorporating grey literature into the systematic reviews to provide a robust understanding of the topic which could address the second limitation. In addition, future systematic reviews could focus more specifically on just one question for the review (e.g. what are the risks to CI as discussed in the literature?), as opposed to the broader questions posed in this review which could provide an in-depth understanding of more specific areas of the concept.

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Appendix

Appendix A

Initial Codebook Developed

Node	Sub-nodes
Resilience definition	
Measuring resilience	
Assessing resilience	
Types of resiliency	Engineering Ecological Complex Adaptive Systems Social
Frameworks	Theoretical Empirical
Models	Theoretical Empirical
Case studies	
Vulnerability definition	Exposure Hazard
Resiliency indicators	
Hazards (to CI)	Flooding Terrorism All-hazard
Geographic regions	
Interdependencies/dependencies	
Environments	Urban Rural
Climate change	
Types of infrastructure	
Stakeholders	
Public policy tools	

Environments	**Urban** **Rural**
Climate change	
Types of infrastructure	Communication Energy Financial Public Health Stormwater Transport Water