

The evolution of resilience from its ecological roots to critical infrastructure applications: Concepts, definitions and future directions

Dionysios Nikolopoulos^{*} , Christos Makropoulos

Department of Water Resources and Environmental Engineering, National Technical University of Athens, Heroon Polytechniou 5, GR-157 80, Zographou, Greece

ARTICLE INFO

Keywords:

Resilience
Critical infrastructure
Deep uncertainty
Strategic planning
Policy

ABSTRACT

Critical infrastructures (CI) in the water, energy, communication, transportation, and other sectors, are increasingly exposed to multifaceted hazards, ranging from extreme weather events to cyber-physical attacks, as well as unprecedented environmental, socioeconomic, institutional and technological changes, that challenge the traditional “fail-safe” design paradigm. This review article traces the evolution of the concept of resilience from its ecological and material science origins to its modern policy mandate in the planning, design, and operation of critical infrastructure systems against uncertainty. Various interpretations of resilience are examined and contextualized along other related, but different policy terms, like risk and sustainability, with which resilience is often conflated. Inherent traits or designed properties of systems that contribute towards resilience are also explored. The discussion highlights key challenges in operationalising resilience through quantifiable metrics while acknowledging the steps already taken to incorporate the concept into standards and policy. It is further argued that adopting a “stress-testing” approach to resilience quantification is an intuitive and powerful way to generate evidence-based resilience assessments. The need for cultivating a more “uncertainty-aware” design and management culture in the CI sectors is also discussed, and the critical role resilience has to play in such a culture is presented, as a direct, tangible response to the deep uncertainties that are emerging in the global physical, social and geopolitical landscape within which CIs are tasked to operate.

1. Introduction

“Individuals die, populations disappear, and species become extinct”, reads the opening line in Holling’s [1] seminal paper on ecologic resilience. And, like most human activities, works and concepts that imitate their natural counterparts, engineering works do *fail*: it is only a matter of *when*, and *how*. Critical infrastructure (CI), which includes water, energy, communication/ICT, transportation, supply chain and other systems, is no exception. From extreme natural phenomena that lead to calamities, to structural failures, human errors and accidents, or deliberate malicious actions like cyber-attacks, there exist innumerable possible vectors of failure for CIs. And, in the era of ever-increasing interconnectivity and interdependency of infrastructure, this may induce significant cascading effects, so *what else* might be impacted becomes a new important subject. The traditional engineering approach to this problem was to over-engineer systems against “all” predicted or projected eventualities for the design horizon, typically accounting for uncertainties with large safety factors [2], in an effort to create “fail-safe” systems. Reality has shown that this design paradigm is

not only overly expensive, but inevitably futile, while radiating a false sense of reliability [3,4] to engineers, decision makers and the public alike.

The are several reasons for this ‘fail-safe fallacy’. One important factor is the actual “persistence” in time of infrastructure; Planning and management activities contend with the provision of service against future uncertainties. Effects of decisions or design options can be lasting, as the system ultimately must endure stresses and changes over several decades. Although the typical design lifespan of most CI ranges between 25 and 50 years (e.g., water supply systems, electric grids, dams), the actual average lifespan is usually much longer. At least in the developed countries, most urban infrastructure was built between 1930–1980, and is already reaching or even surpassing the original plan. The extreme case is in early industrialized cases (UK, USA, France, Germany, etc.) where there are CIs already over a century old, e.g., water supply systems [2,5], such as London’s water distribution system, where almost 60 % of pipes are over 60 years old, with the oldest pipes unearthed dating back 150 years [6]. Typically, original systems retain the older core and expand along with urban sprawl, rising demands and growing

^{*} Corresponding author.

E-mail address: nikolopoulosdio@central.ntua.gr (D. Nikolopoulos).

<https://doi.org/10.1016/j.ijcip.2026.100848>

Received 24 March 2025; Received in revised form 4 February 2026; Accepted 14 March 2026

Available online 15 March 2026

1874-5482/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

population. This almost continuous expansion creates significant path dependencies: technological (new technologies that should seamlessly merge with older existing infrastructure), economic (heavy investments, low return rate, long amortization periods) and societal (public but also institutional entrenched cognitive and normative biases about a system's valid form and function) [7–10], that impose burdens and lock-ins in the process of changing the way we design and operate critical infrastructure.

In addition to the aging infrastructure that becomes less reliable, there is also the threat of an aging workforce. A large percentage of the current workforce (experienced engineers and technicians) in long-held positions are retiring, and institutional knowledge about the systems they designed, developed, installed and maintained throughout the years is leaving the industry along with them [11].

The longevity of CIs means that ultimately these CIs would have to face significantly different conditions from those considered in their planning phase. This is especially true in the current volatile environmental and socio-political landscape: Significant direct (e.g., climate change) and indirect (e.g., pandemics such as COVID-19, the current Russo-Ukrainian war and the energy crisis that ensued, supply chain problems) stressors affect CIs, either gradually (transpiring over time – chronic) or abruptly (occurring over a brief period – acute) [4,12,13] and are fast becoming the “*New Normal*” [14]. As such, decisions regarding the development of new, or the upgrade of existing infrastructure, needs to be considered within a context of *deep uncertainty* [15]. The global natural, social and technical environment is rapidly changing at unprecedented rates [4,16], leading to higher levels of uncertainty, and disturbance to infrastructural systems. Thus, the assumption of stationarity in natural systems, is effectively undermined. Stationarity has been fundamental for *traditional* infrastructural system design and management [17], utilized for example when quantifying return periods, risks, failure rates etc.

Abandoning the stationarity assumption means that the amplitude and frequency of extremes increases with global environmental change [18,19]. Historically observed data for climatic variables may no longer be adequate to meaningfully plan for climate variability and extremes like floods [20] or for operational management of water-energy CIs [21]. Moreover, a variety of interdependent socioeconomic *challenges* and *stressors* arise, that are also not stationary and difficult to predict for planning and management, including population growth urbanisation, demographic shifts, change of living standards, and immigration due to armed conflicts, economic crises or climate change. Many of these factors are totally outside the sphere of influence of CI decision-makers.

Along with their external environment, the very nature of many CIs (e.g., in the water and energy sector, where industrial processes are common) is also rapidly transforming. The physical processes are monitored coordinated, and controlled by a networking, computing and communication core [22], usually achieved in real time via feedback loops, where physical processes affect computations and vice-versa [23]. This integration of physical processes with computational engineered systems forms a cyber-physical system (CPS) [24]. Contemporary industrial control applications are evolving rapidly benefiting from the emergence of other related technologies in the informatics and computer science fields, such as AI (artificial intelligence), IoT (internet of things) and Industrial IoT [25], smart systems philosophy, Machine-to-Machine (M2M) [26], Big Data [27], cloud [28] and fog [29] computing, new sensor technology [30], and other advances in ICT like widespread optical fiber wire connections and 5 G cellular connectivity [31]. These technologies, among others, allow the forming of true completely integrated, always online, smart, highly autonomous real-time analysed monitored and controlled CPSs, deeply connecting the physical with the information world [23]. The unprecedented rate at which CPSs are penetrating domains of infrastructure and revolutionizing industrial applications has led to the adoption of the term “the fourth industrial revolution” or Industry 4.0 [32]. Besides the many advantages, the cyber-physical nature of CIs significantly expands the

“attack surface” [33]. Alongside the millennia-old possibility of infrastructure sabotage as a hazard, a new emerging threat is cyber attacks, which can take a variety of forms, such as malicious remote control, manipulation of transmitted signals/readings, interruption of service, malware etc. Cyber attacks at a CPS can potentially have dire physical consequences that arise from the disruption of operations, and these attacks are termed *cyber-physical attacks* [34]. Notable examples in CIs are the “Stuxnet” attack at a nuclear power plant [35], the “Sobig.F” worm infection at a US railway company [36], the Ukraine power grid attacks [37] and the Maroochy Water Services hack [38], all of which had significant physical consequences in CIs of different domains.

We can deduce, that driven by challenges and changes associated with large-scale, long-term uncertainty, the future performance, efficiency, capacity, reliability and security of CIs are expected to change in an unprecedented rate and magnitude. Nonetheless, we can brace ourselves and accept the predicament, finding solace in the ancient proposition of the pre-Socratic Greek philosopher Heraclitus in ca. 500 BCE, that “change is the only constant in life”. The associated uncertainty about future evolution of conditions is neither abnormal, nor a totally new engineering concept. Thus, it is evident that the “fail-safe” system design aspirations against all eventualities are increasingly rendered unrealistic, and a paradigm shift is needed [39]. Contemporary scholars argue that water system design logic should transition towards “safe-to-fail” systems [4,40,41], which anticipate failures and are prepared to overcome them. Pivotal to this paradigm shift is the concept of system resilience. Despite the volume of research and practice efforts, resilience remains a rather elusive term in interpretation and quantification, without a clear consensus for operationalized definitions [42]. Nonetheless, generally the various emerging resilience theories and concepts are all about coping with the unexpected and continuing to perform under uncertainty. On the other hand many scholars (e.g., [43–45]), criticize that resilience has been vague, intertwined and confused with other policy terms such as sustainability, vulnerability and risk, and sometimes used to promote conflicting policy agendas, risking turning into a ‘buzzword’. In this article we will thoroughly examine the trajectory of resilience to academic and practice popularity, its interpretive evolution through osmosis with various domains, and explore how it can be utilized as a useful design philosophy concept for CIs and engineering systems in general, besides the challenges in formally describing and quantifying it.

2. Explaining the current prevalence of resilience given its evolution from antiquity to its socio-ecological roots

2.1. The rise of resilience to policy and practice stardom

The term “resilience” has prevailed in policy discourse across a multitude of domains, both in academia and practice [46–50], evolving through time in a multi-disciplinary term [13]. An indication of the dominating nature of the term in academic publications is demonstrated by the (almost) exponentially increasing volume of related publications in Fig. 1. Contrasting its popularity, resilience remains a rather elusive term in definition, because there is a conceptual fuzziness to it [49]. The term has been abstract and malleable enough to be involved into everything from research to governmental policies within the worlds of finance, organizations, critical infrastructure, urban communities, defence and ecological systems among others [51]. As such, the term functions both as a “boundary object” between scientific domains - an entity shared by several different communities but viewed or used differently by each of them [52], allowing interpretive flexibility and definition negotiations [53] - and a “bridging concept” which actively links fields and stimulates communication and collaboration, fostering interdisciplinarity and transdisciplinarity [43,54,55]. The associated vagueness though can make resilience difficult to operationalize and develop general indicators or metrics [56–58]. Nonetheless, policy makers around the world have widely and openly adopted the term into

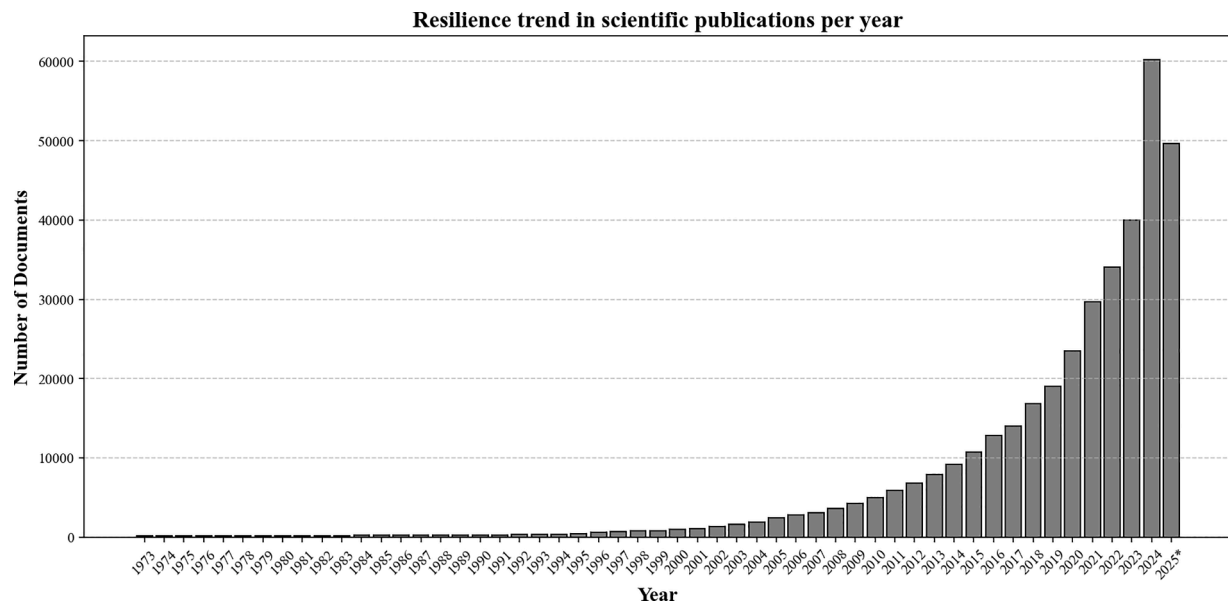


Fig. 1. Indexed scientific publications per year (376,114 up to 06/08/2025) in the Scopus database that include the terms *resilience*, *resiliency* or *resilient* in the title, abstract or keywords. Year 2025 is incomplete.

virtually every aspect of decision-making processes, such as disaster management for communities, national security and critical infrastructure protection. Some notable examples include the Critical Entities Resilience EU Directive, Presidential Policy Directive 21 for Critical Infrastructure Security and Resilience [59] in the USA, the UK Government Resilience Framework [60] in the UK regarding civil contingencies law, The UK Water Act 2014, where a prime duty is to secure resilience of the water sector [48], and the 17 Sustainable Development Goals by the United Nations, where resilience building is a pivotal theme. This widespread usage, especially in a regulatory context, is what prompted some scholars to note that often resilience is employed to justify diverse and even conflicting goals, as part of political agendas [43,58,61–63]. To better understand however this trajectory, it is imperative to explore the evolution of the term.

2.2. Resilience roots

The history of resilience is interesting, long, and diverse. Etymologically, it stems from the Latin word *resilio* or *resilire* [57,64,65]. The prefix *re* is added to the verb *salire*, which shares its root with the Ancient Greek word *ἀλλομαι* and means “to jump back”. Pizzo [57] reports that the earliest occurrence of *resilire* can be traced back in the only known work of the Roman poet and philosopher Lucretius, *De rerum natura - On the Nature of Things* (c. 60 BCE), specifically on a passage in Book IV, lines 311–313, that refers to the reflection of things on a mirror:

Latin: Omnia quandoquidem cogit natura referri ac resilire ab rebus ad aequos reddita flexus.

English: Nature constrains all things to be carried back, and leap back from things, sent back at equal angles (Translated by Bailey [66])

Alexander [64] reports on more references to *resilire/resilio* in the Classical times within the writings of Seneca the Elder (in imaginary legal cases in the sense of “leaping”), Quintilian (in the rhetoric textbook *Institutio Oratoria*, as “to avoid”) Pliny the Elder (in the encyclopaedic work *Natural History* as “leaping of animals”), Ovid (in the *Metamorphoses* poem, used as “to contract/shrink”), Cicero (in *Orations*, as “rebounding”, notably here in a negative connotation) and Livy (in the *History of Rome*, as “springing back”). The term also appears in Middle French (the official language in the Kingdom of France in place of Latin between the 14th and 16th century) as *résiler* before migrating

to English as *resile*. The word appears in State Papers by King Henry VIII in 1529 about troubles with his first wife in the sense of “retract”, “return to a former position” or “desist”. In 1625, the noun *resilience* appears probably for the first time in a scientific sense, i.e., about the strength of echoes, in *Sylva Sylvarum* of Sir Francis Bacon. Interestingly, another form of the noun, *resiliency*, still sporadically found in the scientific literature, also appears during the 17th century.

Resilience is introduced in engineering scholarly works in the 19th century, initially in the domain of material science, when describing the property of timber types (for ships) to resist sudden loads without breaking by Tredgold [67]. Robert Mallet, an Irish civil engineer discusses the “modulus of resilience” as a new coefficient of strength to assess the ability of materials to withstand severe conditions, e.g., explaining the sudden destruction of artillery units in service [68], assessing the suitability of building materials and explaining the devastation caused by the Great Neapolitan Earthquake of 1857 in Naples [69,70] and the study of iron plates used in naval ships [71]. Other definitions were also introduced regarding material properties [72,73], such as “the capacity of a material to withstand work that may be performed upon it, within the elastic limits”, similar to modern definitions like “the quality of being able to store strain energy and deflect elastically under a load without breaking or being deformed [74] or “the ability of a material to absorb and release energy, within the elastic range” [75]. Within the material science domain, resilience continues to be a well-defined concept for a very long time [76]. Thus, resilience already possessed a long-standing engineering heritage, that metaphorically alludes to the modern usage, before being a “reborrowed” term from the socio-ecological scholarly works, that are often seen as the “origins” of system resilience thinking.

Another long-lasting use of resilience occurs within the mental health and psychology domains. Here, it was used from the 1950s in developmental research to describe the ability of children to cope with trauma, disasters and other adverse situations, continue psychological and cognitive development, being able in the long run to attain a normal adulthood [77–81]. Interestingly, resilience in the context of ‘resilient children’ (who can recover from stress) was introduced as a substitute term for the extreme notion of the ‘invulnerable children’ (who are by nature unaffected from stress) that saturated the early influential works in the domain [82,83]. This paradigm shift in the psychology domain analogously resembles the emergence of the term resilience in the shift of engineering design paradigms from ‘fail-safe’ (i.e., invulnerable) to

'safe-to-fail' (i.e., resilient) systems. In later works, the usage of the term broadened to encompass the ability of adults to manage abnormal situations, such as wars, disasters, traffic accidents etc. [76]. For example, Bonanno [84] defines *adult resilience* to loss and trauma as "the ability of adults in otherwise normal circumstances who are exposed to an isolated and potentially highly disruptive event such as a death of a close relative or a violent life-threatening situation to maintain relatively stable, health levels of psychosocial and physical functioning". Also, resilience within the domain is often understood not only as a personal trait but also as a process where "positive adaptation" occurs within the context of significant adversity [85,86]; again a similar concept, resilience as a process or an outcome, can be found in the literature of system analysis [87], showing how different fields evolve following the same concepts. On a similar manner, anthropologists also used resilience to change to describe human adaptation to adverse environments [88]. Finally, note that adaptation is yet another term used interchangeably between disciplines; as elaborated later, adaptation when facing perturbations/stress is a very common resilience goal or desired trait in the general resilience theory for systems.

Since the 1970s, the term resilience has been extensively used outside the mechanics/material science for properties of an object/component or the psychology of an individual, in another, broader metaphorical sense [89], concerning whole 'systems' in various domains [48,57,65,90]. This is a turning point for the upsurge of the term in literature, as it is linked with the *system analysis* and *system thinking* approaches. All this sparked from a seminal paper of the theoretical ecologist Holling [1], in the context of ecological systems in phase space returning to an equilibrium state, after a perturbation. Resilience was contextualized as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables"; and Holling suggested that a population's resilience property is a more important characteristic of its ecological viability than the population count at some moment in time. This definition and variations of it is virtually referenced in all related literature [42] and marks the dawn of a systemic approach, in contrast with individualist-trait definitions.

Moreover, Holling contrasts and differentiates resilience from stability in ecological systems, suggesting that very stable systems (i.e., exhibiting low variability of species densities over time) may not be able to cope with sudden large variations in population densities after perturbations, in contrast with systems that exhibit unstable behaviour with wide variability ranges, which may ultimately persist severe shocks. Holling illustrated the existence of multiple stability domains that form after perturbations (referring to them as "basins of attraction"). That idea challenged the mainstream ecology body at the time, which proposed a more static understanding [91,92], i.e., in the past a single stability domain for the equilibrium state was proposed for ecosystems because these were conceived as inherently stable and predictable [93] – and thus, infinitely resilient, able to return to equilibrium after human stressors were removed from the environment [91]. This notion of resilience versus stability was explored shortly after in a water-resource context [94] and in water resource planning [95]; there, arguments suggested that in engineering resource systems, imposing stability - by specifying standards for the system to strictly adhere to, for example completing design objectives with probabilities close to unity - could end up restraining the system with high mis-allocated costs. The reason is that systems can be exposed to unknown threats, for which no probability of occurrence can be assigned, pertaining to the uncertainty problem for the future provision of systems performance.

Interestingly though, work regarding ecological resilience at the time continued to focus on implicit assumptions of a single stable state for systems [91], and ignored non-linear dynamics and other complexities, because of the difficulty in demonstrating shifts to multiple stable states in the real world. In that context, resilience was interpreted and measured in many studies as the return speed to this single equilibrium after disturbance [96–99]. This notion influenced the resilience

conceptualization in other fields too, as for example in water resource systems, with the seminal work of Hashimoto et al. [100], where resilience describes the speed of transition from a failure state back to a satisfactory state – calculated probabilistically, as the inverse of the average time periods a failure state is expected to last. Holling [40,101] proposed that this return speed to equilibrium metric should be termed "engineering resilience" to differentiate from "ecological resilience" due to the divergence in the scope and objectives of the implementation of the term with regards to the "stability" concept (not to be confused with whether the implementation is within the "engineering" or "ecological" domains). Engineering resilience focused on "maintaining efficiency of function" and stability near the assumed or designed global equilibrium, used predominantly by engineers with the motive to optimally design single-objective 'fail-safe' systems. On the other hand, ecological resilience, focused on "maintaining existence of function", acknowledging the fact that disturbances can force systems to flip between various different equilibrium states, commonly used by biologists and ecologists who search for 'safe-to-fail' systems. In that sense, ecological resilience evolved (slightly) from the 1973 definition to account for the emergence of different stability domains after perturbation as the "ability to adapt to change by exploiting instabilities" [102] and not just absorb disturbances.

In other words, resilience morphed into more general definitions (with Holling as the leading author or co-author in joint works with other colleagues) that include the possibly lasting aftermath of the perturbation, like "(the measurement of) resilience is the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour" [40] and its subsequent evolutions: "Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" [103]. In the work that introduced the latter definition, there is also the important note that even though the interpretation of 'engineering resilience' as the return time to equilibrium is indeed related to the system's resilience, it cannot encapsulate all failure modes (permanent or temporary) for systems and the retaining of functions at these modes, because of the possibility of multiple stable states after disturbances and perturbations. This definition is used commonly in the literature, in many domains besides ecology, albeit sometimes with small variations in wording [19,104–107].

The concept of 'ecological resilience', as elaborated through the aforementioned works, permeated a great variety of interdisciplinary work about societal (human) – ecological (biophysical) interactions, in what is called socio-ecological systems (SES) [108]. Indeed, the definition of Walker et al. [103], concerns management of SES – not just ecosystems in the wild. In SESs, the 'adaptive cycle' is another very important aspect of resilience and reflects the learning aspect of the system behaviour [56,103,104,109–112]. In that sense, in many works that refer to resilience essentially within the context of the aforementioned definition, add explicitly the ability to learn and build adaptive capacity to the wording of the definition e.g. [109,113,114].

The concept of "panarchy" (coined as an antithesis to the term hierarchy), i.e., the idea that systems constantly change under adaptive renewal cycles and nested cross-scale dynamic interactions of human and nature, introduced by Gunderson and Holling [110] laid the foundations of the modern dynamic characterization of social-ecological resilience. In this concept, the cycles consist of four stages: the phase of "growth and exploitation" that slowly merges into "conservation", where the system dynamics are predictable, the chaotic "collapse or release" following perturbation, and the "renewal or reorganization" phase which may culminate into a different system version. Carpenter et al. [109] view this concept of adaptive cycles as a useful metaphor in order to gain insights about system behaviour under cross-scale dynamics and form a theoretical approach towards system-specific operational definitions of resilience.

2.3. Resilience sprawl to other fields examined from bibliographical data

Besides studies in material science, mental health, ecology and socio-ecological systems (SES), the term has emerged in various fields, including:

- Natural hazards/natural disasters community resilience [65,89,115–120], as for example seismic resilience [121,122] or the related domain urban resilience [123,49], including resilient urban planning [3,124] and resilience against other human-induced disasters like terrorist attacks [125];
- Adaptation to environmental or climate change [112,126–128];
- Landscape geomorphology [129];
- Agricultural systems and their management [130–134], with an active subdomain of tree resilience [135,136];
- Infrastructural systems [137] or general engineering systems [138], like water distribution systems [139–141], and including Critical Infrastructure Protection [59,142];
- Complex network resilience [143] like the cases of a) power grids [144,145] or microgrids [146,147] and general energy service security [148–150] or b) the Internet [151,152];
- Cyber-physical system security [153];
- Organizational resilience [154–161];
- Supply chain resilience [162–166], which as expected is actively linked with the recent Covid-19 disruption [167,168];
- Regional economics [169];

To examine this sprawl, besides reading a lot of the literature, the authors also used available bibliographic data downloaded from the SCOPUS database to conduct a bibliometric study that used state of the art computational and natural language processing models. Fig. 2 presents a schematic outline of the methodology.

The corpus under study amasses a complete snapshot of the documents that feature the terms “resilience”, “resilient” or “resiliency” in the title, abstract or keyword fields till year 2024. For the incomplete at the time of writing, year 2025, the 5000 most cited documents have been incorporated into the corpus. The bibliographic information (including abstracts, keywords and the references of each document) is

downloaded in the form of .csv text files. These are loaded into a pandas dataframe [170]. Subsequently, the corpus is cleaned from duplicates, papers that have been retracted, as well as documents that are notes or erratum, producing a vast dataframe of 315,251 documents (Table 1), which is challenging to analyse.

The text comprised of the title, abstract and author keywords is provided as an argument to a Sentence Transformer model (SBERT) [171], in order to create embeddings from the text for semantic search. From the available pre-trained models we used ‘all-mpnet-base-v2’, which is considered the most performant. The embeddings generated are in the form of vectors with 768 dimensions and can be compared for semantic similarity. The process is sped up via GPU (graphics processing unit) acceleration.

The k-means algorithm [172], as implemented in SciPy [173] is used to create semantic clusters of the documents, based on their embeddings. The number of clusters is set to 25. To identify semantically the general topic of each formed cluster, the Latent Dirichlet Allocation (LDA) technique is utilized [174], through the gensim package [175]. Table 2 presents the topic keywords (up to ten, with singular/plural forms merged) and the number of documents per cluster, showcasing the effect resilience has on heterogenous subject areas. A general domain has been attributed to each cluster for grouping. In order to be able to visualize

Table 1

Number of documents per type in the collected SCOPUS dataset.

Type of document	Number of documents
Article	201,920
Conference paper	53,497
Book chapter	25,641
Review	19,630
Book	4443
Editorial	2940
Conference review	2626
Letter	920
Short survey	647
Data paper	148
Report	9
SUM	315,251

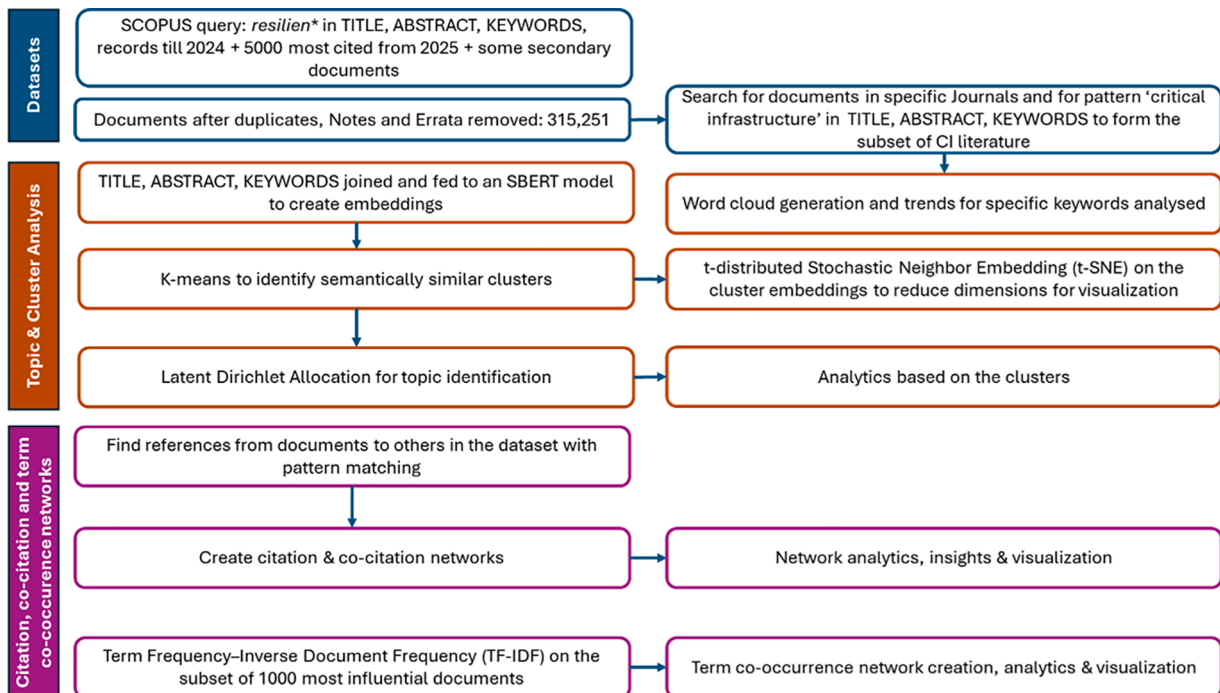


Fig. 2. Schematic outline of the analysis of the bibliographic data.

Table 2
Topic keywords per cluster.

Cluster	Documents	Pct. of documents	Topic Keywords	Domain
0	16,010	5.08 %	network, system, control, distributed, performance, communication, routing, service	Technical
1	14,468	4.59 %	disaster, risk, community, management, social, natural, health, recovery, analysis	Socioecological
2	13,071	4.14 %	seismic, design, performance, concrete, modulus, analysis, structural, asphalt, pavement, strength	Technical
3	18,940	6.02 %	health, child, social, mental, family, psychological, factors, adolescent, risk	Mental health
4	14,142	4.49 %	species, forest, climate, ecosystem, change, soil, vegetation, management, fire, forests	Ecological
5	12,616	4.00 %	climate, change, environmental, management, development, social, adaptation, sustainable, water, systems	Socioecological
6	9879	3.13 %	water, climate, flood, change, management, risk, urban, analysis, system, model	Socioecological
7	14,393	4.56 %	security, system, attack, network, key, detection, learning	Technical
8	7994	2.54 %	cell, protein, human, animal, disease, gene, stress, drug, expression	Biological
9	4386	1.39 %	video, error, coding, image, transmission, channel, systems, wireless, quality, communication	Technical
10	13,010	4.13 %	economic, financial, development, crisis, business, analysis, social, market, policy, impact	Organizational
11	14,944	4.74 %	health, students, psychological, burnout, stress, work, education, care, nursing, learning	Organizational
12	5732	1.82 %	soil, microbial, community, bacterial, water, bacteria, environmental, communities, treatment, analysis	Biological
13	12,402	3.93 %	power, energy, system, control, grid, electric, distribution, network, renewable	Technical
14	11,177	3.55 %	food, climate, change, agricultural, agriculture, farmers, systems, production, crop, sustainable	Socioecological
15	19,310	6.14 %	health, psychological, mental, stress, social, life, depression, support, adult, female	Mental health

Table 2 (continued)

Cluster	Documents	Pct. of documents	Topic Keywords	Domain
16	14,462	4.58 %	social, political, women, education, cultural, community, rights, people, human, work	Social sciences
17	13,720	4.34 %	properties, materials, mechanical, strength, energy, performance, surface, temperature, analysis, thermal	Technical
18	12,048	3.82 %	species, coral, ecosystem, change, climate, environmental, marine, coastal, sea, reef	Ecological
19	8402	2.66 %	plant, stress, crop, drought, plants, climate, growth, yield, genetic, breeding	Ecological
20	12,493	3.96 %	urban, cities, climate, development, city, sustainable, planning, change, design, energy	Socioecological
21	17,565	5.57 %	learning, system, neural, model, performance, control, network, networks, design	Technical
22	12,426	3.94 %	health, pandemic, care, mental, social, disease, psychological, human, stress, coronavirus	Mental health
23	7567	2.41 %	stress, brain, animal, disease, cognitive, male, social, depression, human, behavior	Mental health
24	14,094	4.47 %	supply, chain, management, system, risk, analysis, model, network, industry	Technical

the clusters in a 2D space, the dimensionality reduction technique t-distributed Stochastic Neighbor Embedding (t-SNE) [176] is employed on the embeddings. Fig. 3 presents the clusters in the reduced 2D space, along with the top three extracted keywords from each cluster.

In order to map the citation network of the dataset, it is required to match efficiently the references of each document with the index of the referenced items within the corpus. We employ a custom finite state pattern matching machine that leverages the Aho-Corasick algorithm [177] which has been widely used in bibliographic search. The automaton is built using the titles of all documents, and in linear time searches for potential matches creating lists of referenced indices. To avoid some false positive matches due to erroneous information in the dataset, potential matches are also checked via their year and fuzzy matching the name of the first author. Then, using the NetworkX package [178] we create the citation network as a directed graph (a subset of which can be seen in Fig. 4), with nodes representing documents and edges the references (edge starting at A and ending at B means A cites B). The network graph produced, G , has a lot of separate subgraphs (134,657 subgraphs with 142,631 documents) with many documents neither referencing nor being cited by the other in the collection. These are mostly newer documents with 76.5 % of them published after 2015, showing that resilience in the last 10 years is perceived as a well-established and popular term, used frequently without citing older literature. The largest connected component of the network, G_L , is a subgraph that measures 172,665 items (54.8 % of the dataset), containing the most cited and influential body of literature, possessing a collective h-index (an h number of documents exceeding h number of

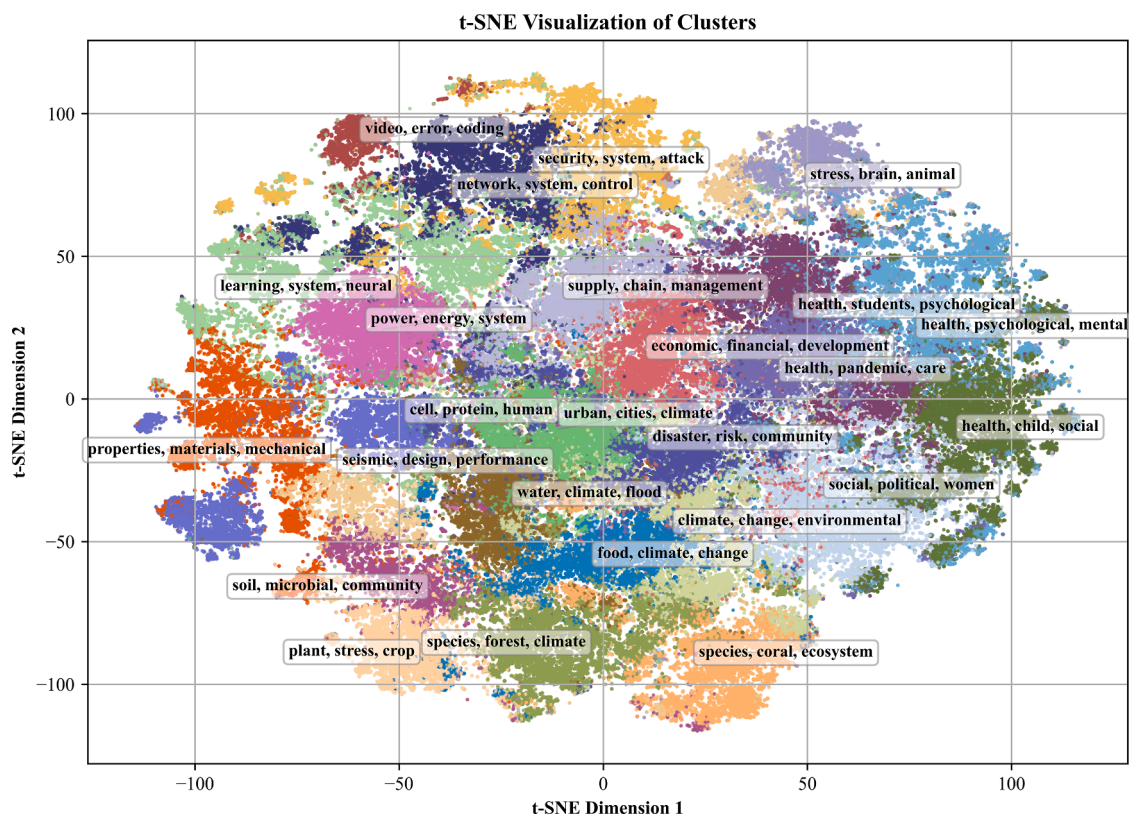


Fig. 3. Visualization of the clusters in two dimensions using t-SNE and top three terms appearing in each.

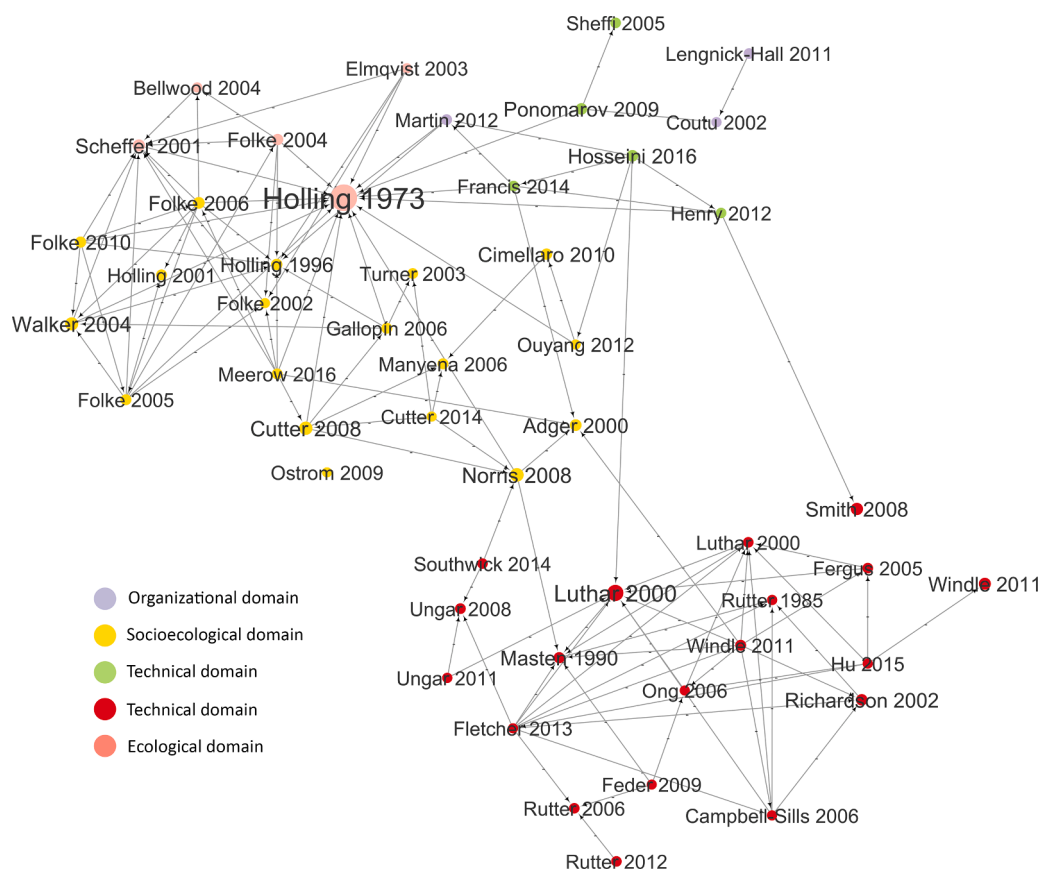


Fig. 4. The citation map of the top 50 most influential documents of the collection, node size according to direct citations.

citations) of 624, compared to the value of 639 when examining the whole network (the remaining documents have an h-index of 273). Table 3 presents the 50 most cited documents in G (all of which are part of G_L as well). The represented clusters in this subset are 5 (22 %), 3 (18 %), 15 (18 %), 1 (12 %), 24 (10 %), 4 (6 %), 18 (4 %), 11 (4 %) 23 (2 %) and 20 (2 %). In the table, citations within the corpus denote citations to document A directly within the dataset collected (i.e., in degree of node A), second degree influence indicate influence of the document A via accounting for a document C citing document B that cited A, first and second degree influence is the sum of in degree and second degree relations, while ancestors counts all nodes in the directed graph that have a reference path towards A, showing the indirect long term influence of a document. The seminal importance of Holling's work can be validated from the fact that it influences directly or via second degree 34,570 documents (10.9 % of the corpus) which is the highest value, while a reference path to it can be traced from 83,163 (26.4 %) documents. Interestingly, due to G_L being highly connected, in terms of ancestors, other documents from the mental health domain attain higher values, as there are both inter- and extra- domain traces to them, but mental health documents tend to be more topical in references (seen also in Fig. 4). Table 4 presents the top 50 co-citation pairs (when a document C references both A and B). Holling's work again dominates the co-citations, interestingly with frequent pairing with works dealing with adaptation. In the co-citations it is evident that documents from organizational, technical, ecological and socio-ecological domains are often co-cited, whereas mental health documents are not. In Fig. 4, a small part of the G_L graph is presented, with nodes from the 50 most influential documents to showcase the relationship between them and their domain. Remarkably, the domains of mental health and socio-ecology even not conceptually similar are connected via documents that are interdisciplinary approaches and reviews on the subject, displaying the osmosis in the literature even by examining a very small subset of it.

A term co-occurrence map is generated from the subset of top 1000 most influential documents as calculated by the first and second degree influence, to give insights about terms with which resilience is more connected to in the literature. The Term Frequency–Inverse Document Frequency (TF-IDF) method is employed through a vectorizer function in the scikit-learn machine learning package [222], to identify the most important words in the subset by balancing their frequency in a specific document against their commonality across the subset. In this analysis very common words in articles like ‘review’, ‘results’, ‘proposed’, ‘according’, were filtered out, after a first pass of the process to keep semantically valuable terms. The highest occurrence rates are by terms *supply*, *social*, *risk*, *system(s)*, *management*, *supply chain*, *stress*, *change*, *ecosystem*, *psychological*, *ecological*, *climate change*, *disaster(s)*, *urban*, *health*, *development*, *community*, *network*, *environmental*, *adaptation*, *vulnerability*, outlining the multitude of different fields where resilience thinking is applied. Comparing the co-occurrence of the top 120 terms in this subset's documents also uncovers three main clusters that outline broader subject matters, as presented in Fig. 5. In this regard, there is a cluster of terms, presented in yellow colour, that relate more to the domain of psychology, mental health social sciences or medicine, e.g., *stress*, *adversity*, *disorder*. The purple-coloured cluster consists of terms like *ecosystem*, *adaptation*, *climate change*, *social*, *urban*, *sustainability* etc., pertaining to ecological and socio-ecological systems. The pink-coloured cluster is formed with terms such as *risk*, *network*, *supply chain*, *management*, *infrastructure*, *uncertainty*, *disruptions*, *design*, *analysis* etc., referring to the broad category of engineering systems, the business, organizational and technological realms and the implementation of technical/practical solutions.

2.4. Insights on resilience research for CI from the available bibliographical data

In order to get some insights about the growing body of CI resilience literature, the subset of CI related documents is attained by pattern

Table 3

Top 50 most influential documents within the collected dataset.

Reference	Cluster/ Domain	Citations within the corpus	Second degree influence	1st and 2nd Degree Influence	Graph Ancestors
[1]	4/Ecological	6756	27,814	34,570	83,163
[86]	15/Mental health	2799	15,607	18,406	82,822
[89]	1/Socio- ecological	1841	9836	11,677	53,164
[117]	1/ Socio- ecological	1740	8055	9795	39,069
[103]	5/ Socio- ecological	1675	11,874	13,549	67,407
[179]	15/Mental health	1340	3325	4665	34,866
[180]	18/Ecological	1291	12,443	13,734	75,071
[181]	15/Mental health	1254	5741	6995	31,037
[91]	5/ Socio- ecological	1136	6970	8106	56,665
[182]	5/ Socio- ecological	1117	10,211	11,328	69,844
[183]	24/Technical	1063	4088	5151	13,538
[184]	15/ Socio- ecological	1046	6835	7881	54,087
[164]	24/Technical	1033	3584	4617	20,322
[40]	5/ Socio- ecological	983	12,320	13,303	79,545
[185]	1/ Socio- ecological	949	4256	5205	28,240
[104]	4/ Ecological	923	6692	7615	66,714
[81]	3/Mental health	922	11,090	12,012	86,544
[186]	5/Socio- ecological	918	5434	6352	42,797
[187]	5/Socio- ecological	836	7816	8652	63,413
[188]	5/Socio- ecological	827	7241	8068	49,072
[189]	1/Socio- ecological	817	8006	8823	45,614
[190]	5/ Socio- ecological	808	6847	7655	65,692
[49]	20/ Socio- ecological	802	2647	3449	11,555
[191]	3/Mental health	796	3593	4389	19,914
[192]	10/ Organizational	786	3600	4386	26,666
[193]	3/ Mental health	752	4163	4915	41,355
[194]	5/ Socio- ecological	747	5671	6418	65,905
[195]	11/ Organizational	720	2608	3328	21,710
[196]	3/ Mental health	702	3705	4407	45,674
[197]	3/ Mental health	697	7901	8598	78,716
[198]	15/ Mental health	693	2762	3455	20,340
[199]	3/ Mental health	690	2470	3160	10,020
[42]	24/Technical	686	4221	4907	18,139
[200]	24/Technical	685	4472	5157	27,948
[201]	3/ Mental health	674	5748	6422	44,923
[202]	24/Technical	624	4248	4872	19,768
[82]	3/ Mental health	591	8450	9041	87,344
[203]	15/ Mental health	578	5274	5852	44,585
[204]	3/ Mental health	575	1827	2402	26,963

(continued on next page)

Table 3 (continued)

Reference	Cluster/ Domain	Citations within the corpus	Second degree influence	1st and 2nd Degree Influence	Graph Ancestors
[205]	15/ Mental health	565	1832	2397	9666
[206]	4/Ecological	558	4964	5522	62,885
[116]	1/ Socio- ecological	558	2842	3400	15,927
[207]	11/ Organizational	552	5009	5561	62,193
[208]	15/ Mental health	543	5213	5756	45,198
[209]	15/ Mental health	534	2330	2864	14,231
[210]	1/ Socio- ecological	532	4015	4547	19,705
[211]	18/Ecological	526	4884	5410	68,060
[212]	5/Socio- ecological	519	7151	7670	70,463
[213]	23/Mental health	515	4073	4588	33,739
[214]	5/ Socio- ecological	512	2400	2912	36,943

matching ‘critical infrastructure’ and its variations in the corpus. Also, items are added from the *International Journal of Critical Infrastructure Protection*, *Journal of Critical Infrastructure Policy*, and *International Journal of Critical Infrastructures*. This narrows the dataset to 3456 documents, which is indicative of recent terminology and multidisciplinary approaches and not exhaustive of the vast body of work on them, since resilience related research has been conducted for systems that are CI (e. g., water systems) across a multitude of journals, and traditionally without the literal usage of the term CI. This is evidenced by the fact that the median year of publication for the CI subset is 2020. Documents pertain mainly to the engineering/technical/urban/community related clusters as expected, i.e., clusters 24 (28.6 %), 1 (17.4 %), 13 (15.1 %), 7 (12.2 %), 0 (9.4 %), 6 (7.2 %), 2 (3.3 %). Interestingly, 2323 (67.2 %) of the documents are part of G_L . The most referenced (with 6 % of documents citing it) document from the CI subset is a review on modelling and simulation of interdependent critical infrastructure systems by Ouyang [223], second (4.7 %) is Holling’s seminal article, and third (4.1 %) a review article on resilience definitions and measures by Hosseini [183]. An interesting word cloud from the abstracts, titles and keywords of the CI resilience documents can be visualized in Fig. 6. A significant number of the unigrams ‘assessment’, ‘framework’, ‘analysis’ and the bigrams ‘risk assessment’ and ‘risk management’ are very frequent signifying the usual system discourse on strengthening resilience. It is also evident that security - particularly cybersecurity -, cyber and physical attacks, disasters, disruptions, failures and vulnerabilities of these systems are frequently discussed. Indeed, a number of high profile publications (e.g., [224–226]) deals with the cyber-physical nature of CI and its resilience against cyber-threats. Fig. 7 presents the frequency over time for some selected terms. The documents dealing with cyber attacks and cyber security are recently increasing, following a previous peak in 2013, perhaps in the aftermath of the Stuxnet incident, and also the term ‘cyber-physical attacks’ has gained some traction. The challenge of climate change and extreme phenomena is also a topic on the rise (e.g., [227]), and the effect of COVID as a major disruption to CI systems is evident from its appearance in >7 % of documents in 2020 (e. g., [228]). Interestingly, the term ‘protection’ is in decline, which may be attributed to a shift in thinking due to resilience, or the connotation of protection mainly with physical hazards whereas cyber threats are becoming more concerning (thus cyber security frequency increases).

Table 4

Top 50 pairs of co-cited documents in the dataset collected.

Document 1	Document 2	Cluster 1	Cluster 2	Co-citation count
[103]	[1]	5	4	768
[1]	[40]	4	5	558
[117]	[1]	1	4	496
[180]	[1]	18	4	490
[182]	[1]	5	4	469
[89]	[117]	1	1	466
[91]	[1]	5	4	459
[89]	[1]	1	4	416
[104]	[1]	4	4	407
[186]	[1]	5	4	363
[190]	[1]	5	4	357
[81]	[86]	3	15	308
[200]	[164]	24	24	291
[189]	[1]	1	4	284
[183]	[1]	24	4	282
[188]	[1]	5	4	276
[103]	[91]	5	5	261
[187]	[1]	5	4	255
[192]	[1]	10	4	249
[103]	[186]	5	5	249
[180]	[104]	18	4	245
[117]	[116]	1	1	243
[202]	[183]	24	24	233
[182]	[91]	5	5	222
[215]	[1]	5	4	221
[86]	[196]	15	3	216
[212]	[1]	5	4	216
[216]	[1]	4	4	214
[49]	[1]	20	4	214
[189]	[117]	1	1	210
[164]	[217]	24	24	209
[86]	[184]	15	15	206
[185]	[218]	1	1	205
[86]	[191]	15	15	202
[42]	[1]	24	4	201
[42]	[183]	24	24	200
[206]	[1]	4	4	200
[65]	[1]	1	4	196
[219]	[202]	10	10	196
[86]	[197]	3	15	196
[220]	[185]	1	1	191
[185]	[1]	1	4	191
[202]	[1]	24	4	189
[179]	[181]	15	15	186
[182]	[103]	5	5	183
[182]	[89]	5	1	180
[103]	[40]	5	5	180
[221]	[185]	2	1	175
[89]	[116]	1	1	174

3. Definitions of resilience

The examination of the co-citation networks and the term co-occurrence networks, supports the notion of resilience emerging from the ecological field, spreading to the socio-ecological systems and then expanded to engineering systems and infrastructure, while in the fields of psychology and social sciences resilience had roots for a longer time. And although these fields are less related to the others, the handling of definitions and concepts shows a great resemblance. In Table 5, a plethora of different definitions of resilience is demonstrated. These definitions, follow a number of re-occurring themes although some definitions can be divided in contrasting groups, i.e., those that focus on the recovery speed following a perturbation versus those that refer to systems adapting to change.

A lot of definitions refer to resilience either as an ability (i.e., a system’s inherent trait) or as a capacity (i.e., the innate potential for a specific characteristic). Although subtle, this difference may relate to systems where there is room to grow a capacity to persist something (the capacity is built, developed or managed by agency) or the capacity exists or not based on the system’s initial design philosophy (for engineered

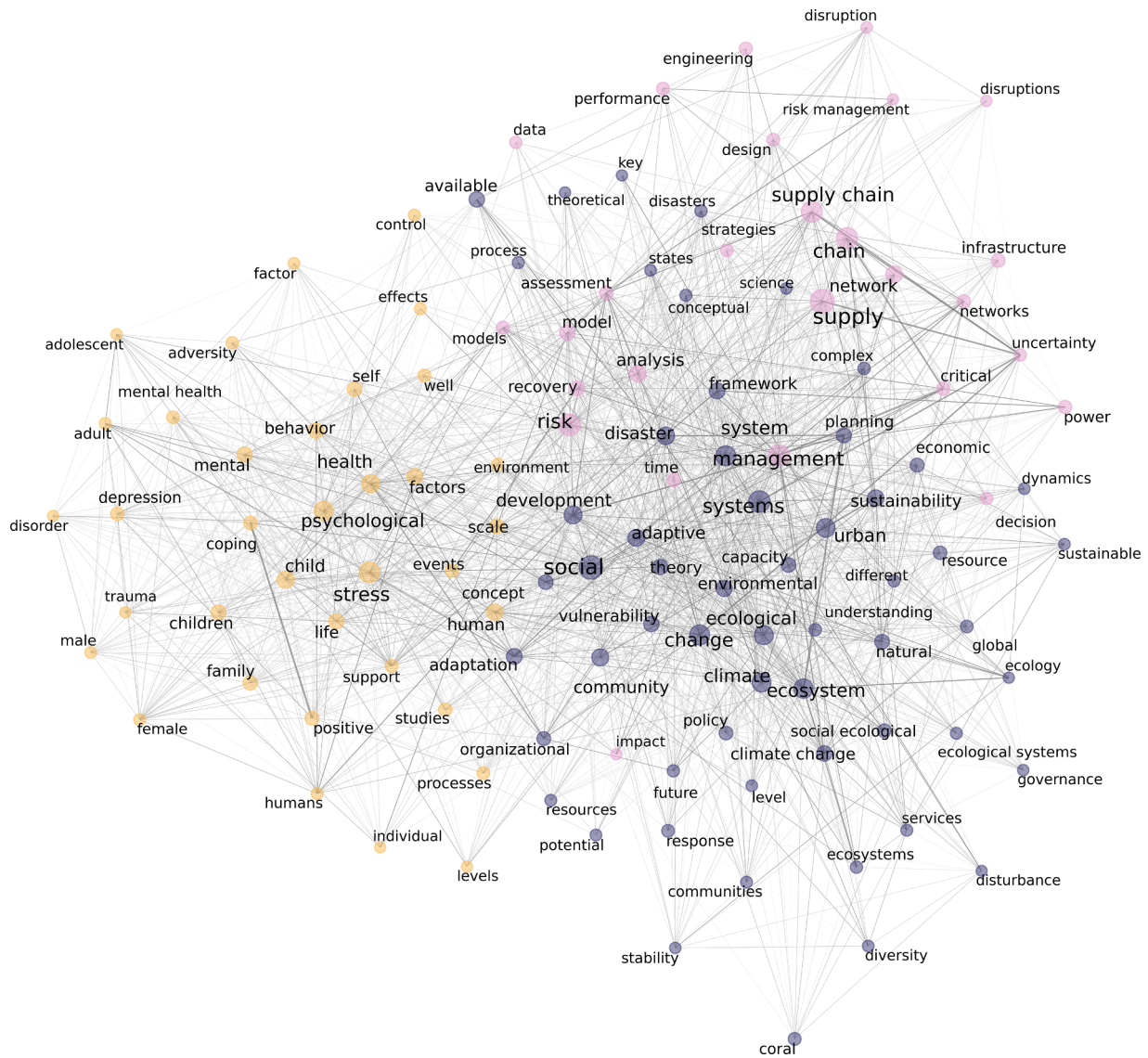


Fig. 5. Top 120 terms co-occurrence network from title, abstract and keyword fields from the top 1000 most influential documents. Edges with heavier weight indicate stronger co-occurrence, while node size is proportional to the occurrence of a term in the corpus.

Critical Infrastructure Resilience Word Cloud



Fig. 6. Critical infrastructure resilience word cloud.

systems) or its nature (for ecological, socio-ecological and other systems). Approaches that are more quantitative refer to resilience also as a measure or magnitude, and such definitions are operationalizable in

specific domains. Regarding capacity, there are usually three frequent themes examined in the literature [236], i.e., absorbing capacity, adaptive capacity and restorative capacity (e.g., [237,238]) and

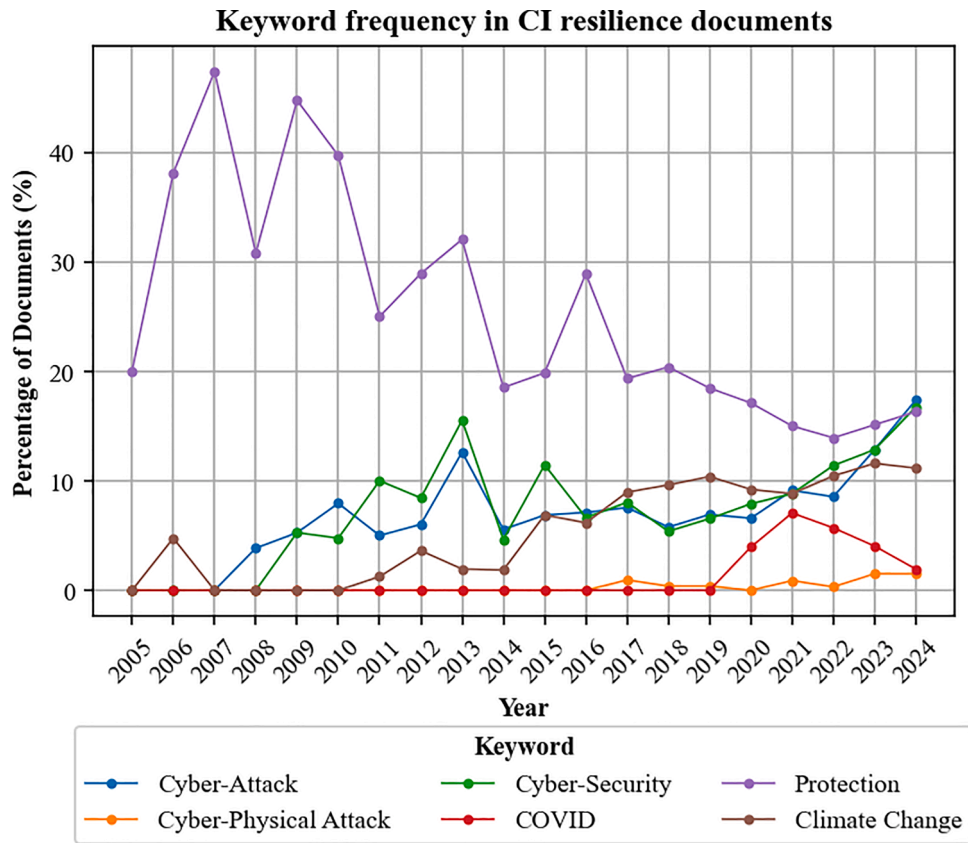


Fig. 7. Keyword frequency of selected terms in the corpus of CI resilience.

sometimes a fourth, withstanding capacity (e.g., [239]).

For absorbing capacity, definitions tend to utilize terms such as ‘sustain’, ‘cope with’, ‘mitigate’ or ‘absorb’ disturbance, referring to the reduction of effects stressors have on the system. A similar concept in some definitions is ‘to maintain structure’. These types of definitions have also resulted in indicators, for example the degree of service capacity reduction with increased pressure in Amarasinghe et al. [240]. Gradual degradation rather than an abrupt failure when absorbing disturbance is also a desired aspect for resilience [233,234]. To quantify this aspect some works utilize failure rates, e.g. via the slope of a decreasing performance curve during a perturbation (e.g., in [237]).

For restorative capacity definitions often refer to ‘recovery’ or ‘return to an operating status’ after perturbations; sometimes these definitions fall on the ‘engineering resilience’ when focusing only on the recovery aspect. Some can be linked with intuitive metrics of recovery speed. Examples in the context of water systems are the definition and quantitative metrics of Hashimoto [100] and Kjeldsen and Rosbjerg [241]. Time-dependent metrics and curves have been also used to quantify resilience in a recovery context (e.g., [210,242] for the electric grid, [121] for seismic resilience). Adaptation capacity is the degree to which systems can adapt to changing conditions [238], and in many definitions of resilience is used as a ‘prerequisite’ for the recovery process.

A number of definitions also include the notion of ‘plan ahead’, ‘prepare’ or ‘anticipate’ stress in their conceptualization, suggesting that resilience is also a pre-emptive, developed characteristic, typically in engineering or infrastructural systems and in the field of urban/community resilience. By introducing preparedness into the system, the ability to cope with disturbance is enhanced. Redundancy-type indicators such as reserve-capacity that can be reduced by disruptions without significant loss of functioning or structure (e.g., [243,244]), are types of metrics used for this, and can be linked with withstanding and adaptation capacity.

Topological or network-based definitions and metrics are also

common in some network-type infrastructural systems as for example in transportation networks [245] and water distribution networks [246], usually measuring performance under failures of some components of the network. In organizational studies, resilience often has an economic connotation in definitions, such as recovery with minimization of associated costs [235,137].

4. What traits enhance resilience?

Throughout the literature, there are various referenced traits that entail a resilient system. However, depending on the context and the scientific domain, these traits shift. The following list presents an effort to describe common interdisciplinary patterns in associating desired system characteristics or design and management principles that improve resilience, ranging from socio-ecological to engineering but also organizational systems:

- **Robustness:** Generally describing an entity’s ability to withstand a given level of stress without any degradation or loss of function, an important trait for resilient systems (see following section).
- **Buffering capacity:** systems that have a capacity in excess of their needs can utilize it when in an emergency, thus being more resilient [232,247].
- **Stability:** A trait that allows systems to cope with disruptions, allowing recovery to the stable domain, increasing reliability, thus enhancing resilience [248]. However, non-stable systems can also be (even more) resilient, as already discussed in Section 2.2.
- **Safe failure (or soft failure):** The ability to absorb sudden shocks or the cumulative effects of slow-onset stress in ways that avoid catastrophic failure, even when outside of design specifications [127] or managing failure in interdependent systems in order to avoid cascading effects [249]. “Rationing” of service (spatially or temporally) to avoid complete blackout is an example for CIs.

Table 5
Examples of the wealth of resilience definitions.

Definition	Source
A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables	[1]
The return time of variables towards their equilibrium after a perturbation, in a stable system	[97]
The magnitude of disturbance that a system can absorb before its structure is redefined by changing the variables and processes that control behaviour	[56]
Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels.	[137]
The capacity of systems to buffer shocks and stresses	[180]
The capacity of an SES to sustain a desired set of ecosystem services in the face of disturbance and ongoing evolution and change	[229]
The ability of a social system to respond and recover from disasters and includes those inherent conditions that allow the system to absorb impacts and cope with an event, as well as post-event, adaptive processes that facilitate the ability of the social system to re-organize, change, and learn in response to a threat	[117]
The capacity to adapt existing resources and skills to new systems and operating conditions	[122]
The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures	[230]
The ability of the system to recover once hazard has occurred and is measured by the duration of the unsatisfactory condition.	[231]
The joint ability of a system to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation	[223]
The degree to which the system minimizes level of service failure magnitude and duration over its design life when subject to exceptional conditions	[232]
The degree to which a system continues to perform under progressively increasing disturbance.	[41]
A system's ability to adjust its activity to retain its basic functionality when errors, failures and environmental changes occur.	[143]
The capability to maintain functions and structure when subjected to internal and external change and to degrade gracefully when it must	[233]
The ability to gracefully degrade and subsequently recover from a potentially catastrophic disturbance that is internal or external in origin	[234]
The ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.	[235]
The ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity	[49]

- **Agility/rapidity:** the capacity of a system for rapid mobilization of resources necessary for recovery in order to return to an acceptable level of functioning, contain losses and/or avoid cascading effects and avoid future disruption [121,250,105,248].
- **Redundancy:** The availability of multiple substitutable components with similar or overlapping functions give a reserve capacity to the system, providing an “insurance” [105] that it will not fail as a whole when a single component fails [125,248,128], e.g., the presence of redundant water quality sensors in a WDN’s contamination warning system or redundant pumps in pumping stations as a reserve. A similar concept in the literature is modularity which besides substitutable components may also refer to the existence of multiple options in a systems to deliver its service [127], or degree to which components can be separated, recombined or reengineered [142].
- **Flexibility:** Due to uncertainties, there might be instances where a system should be reconfigured, and having different options aids a system in adapting to short term changes [105,248]. For example, keeping an old highway active when a new one is delivered, ensures the existence of an additional route to the destination even if it has

lower capacity. Another related term is plasticity, the ability of the system to adapt its structure of behaviour in response to internal or external changes [142].

- **Diversity:** A trait that is similar to flexibility, but describes the degree of multiple distinct functions that can be simultaneously used in the system [105,128], which enhances resilience and aids with perturbations, as there is greater functionality in the system. For example, energy production systems that are diverse in the energy mix (including solar, wind, fossil fuels, hydroelectric energy etc.) can cope with a variety of different changes and easily maintain an acceptable level of service [49]. Another example is a water system having total reliance on a single specific type of water source, e.g., surface water from a reservoir, which may make the system susceptible to failure as climate changes. On the contrary, having the capability to also use alternative sources such as seawater desalination in an emergency, makes the system less vulnerable to prolonged drought conditions. Diversity is also related to multifunctionality, i. e., components of the system that provide a diverse set of functions, such as floodplain parks [3]. Another related trait is ‘omnivory’ [232, 128,247], referring to multiple ways of meeting needs resource-wise.
- **Independence/autonomy:** The self-reliance capability of various components to operate/function without external input, assistance or oversight enhances resilience and levels of a availability in a system, when other components are hampered [125,248]. The autonomy trait can refer to systems as a whole that do not rely on other infrastructure for functioning. This is contrasting with other characteristics in the literature, like *interdependence* and *interconnectedness*, which, depending on the context, can affect resilience positively or negatively [248]. For example, having the ability of interconnection to receive support from other systems in case of failures is beneficial; but in critical infrastructures interconnectivity usually means interdependence which may be detrimental due to cascading effects from one disrupted sector to the other [251–255], e.g., a blackout in an energy production system affecting the pumps of a water supply system, the transportation, the telecommunications sector and the emergency services, like in the case of the 2025 major power blackout in the Iberian Peninsula [256].
- **Cohesion:** the existence of unifying relationships and linkages between system variables and elements [257]. Cohesion also applies to social systems denoting the strength of social connections and the sense of community.
- **Resourcefulness:** Refers to the abundance of resources (material aspect) available to the system for preparation against, response to and recovery from perturbations, also including the capacity of operators, decision-makers planners and other system stakeholders to plan, anticipate and act (human aspect) [121,117,248].
- **Coordination capacity:** A system that possesses good coordination between all relevant managerial stakeholders is able to recover faster from perturbations, as actions can be better planned and organized [127].
- **Foresight capacity:** Resilience is all about tackling future uncertainty; therefore systems where future conditions can be evaluated before they manifest, and different scenarios are analysed in preparation, are more resilient [248]. Related terms in the literature is preparedness [117] and anticipation [156].
- **Collaboration:** the existence of multiple opportunities and incentives for broad stakeholder participation to solve problems [125,248]
- **Adaptability:** the flexibility of a system to change in response to new pressures [257], also entailing the capacity to learn from disruptions and perturbations [109,104,56,110–112,103] and applying the knowledge to undergo change and reduce vulnerabilities in the future [248]
- **Self-organization:** In self-organized systems macro-scale patterns, relations and relations emerge from independent interactions between smaller scale processes [258]. Self-organization capability is often associated with resilient systems (e.g., [259,109,105,260], due

to the fact that actions and functions are distributed among different actors (as for example citizen participation in social systems) and not centralized (in true self-organized systems, typically there is absence of centralized control [261]), thus response and adaptation to events can be faster [105]. Also, self-organized systems exhibit increased social and institutional memory, i.e., collective experience to deal with change [187]. In social self-organization capable systems there is the capability of independent response to disruptions by local communities, cross-scale partnerships for management [187], and both horizontal and vertical institutional connections that foster better informed and more efficient decision making [262,117]. A relevant term, is *flatness* [247], which refers to bottom up systems, with less hierarchical and rigid command chains, which are more flexible and resilient. In technical systems, the mechanically analogous scheme for self-organization and flatness are distributed/decentralized/localized designs and management philosophy (versus traditional large-scale centralized systems) with a multitude of studies that show that this increases resilience e.g., [3,8,144,146,150,248,263–266].

- Creativity/innovation capacity: The property of a system to use disruptions as opportunities for positive gain. This requires the system to possess and innovation capacity and exert it [248]. Innovation strengthens resilience, because it reinforces the transformational capability of the system [186]. The notion of positive gain (or even flourishing) when a system is subjected to adversity can also be found in the literature as the concept of ‘antifragility’ [16,267,268].
- Efficiency: Depending on the context (e.g., for energy systems, economical systems, organizational resilience or in the industrial ecology field), there are scholars (e.g., [257,125,269,270] who find efficiency to be an important trait of resilient systems. However, there are other important yet counteracting traits that enhance resilience, like redundancy and flexibility; generally building redundancy and flexibility in a system hampers efficiency (at least in economic or resource-usage terms), thus resilient systems are not always the most efficient [92], while hyper-efficient systems (e.g., those employing hyper-coherence [271] between functions and components) with the most optimal (but not robust) decisions could actually possess less resilience [215]. An example can be a Formula 1 car compared to a family station wagon; the former is overdesigned to perform as efficiently as possible, but within very specific conditions and ultra-tight maintenance – the latter can withstand a lot more road, environment and driver induced stress, without failures.
- Equity/fairness: applicable in communities and social systems, equity and fairness are important aspects and principles of resilience, coming up regularly in socio-ecological systems, community resilience and in the climate resilience discourse (e.g., [272,110,112,260,58,124], and also in climate adaptation studies; as Nelson et al. [112] note, in decision making there should be equity in both the process and the outcome, referring to the fairness of institutions, their representativeness, views on collective and individual good and in the distribution of vulnerabilities across a population. As such, social cohesiveness increases, which leads to a community’s larger capacity for absorbing and recovering from shocks [248]. Affordability, accessibility and acceptability of technologies, solutions and interventions to transition to a more resilient system, are also related themes to be taken into account assessing equity.

The aforementioned traits can be incorporated into the design and management of CI systems either as developed qualities of the system itself, like for example robustness, redundancy or diversity, or qualities of the surrounding socio-technical environment like resourcefulness, and foresight capacity.

5. Connotations and nuances of resilience when contextualized along other policy and decision-making terms

Through the last decades many scholars tried to establish common patterns in the variations of definitions for resilience, distinguish it from other related terms and/or give an overreaching general description or frameworks for estimation. Throughout these interdisciplinary research efforts, there are a plethora of other terms with which resilience is associated or contrasted.

One term is the multidimensional, interdisciplinary, and global in scope, sustainability [273]. Humanity’s future prospects may be seriously undermined by the plethora of changes amidst the Anthropocene era [274] and rebound effects on societies that stem from human-made perturbations on key earth processes, resources availability and rising complexity of global social-ecological systems [107]. The current development paradigms and patterns, if not transformed, may tip the integrated human-earth system to a radically different basin of attraction – and resilience on the planetary scale can be conceptualized as the depth of the current basin, prohibiting destabilization of the Earth System [275]. The well-known ‘Brundland Report’ in 1987 [276] popularized the notion of sustainable development, meaning “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Developing resilience in our systems plays a pivotal role towards the path to sustainable development [155] and enables sustainability to be viewed as an inherent system property through a perspective of systems thinking, rather than an abstract goal that humanity collectively aspires to [257], and that is why there is broad consensus in the literature that these terms relate [91,103,109,259,277]. For example, shifting the paradigm from centralized structures and open loop designs for water and nutrients to decentralized designs with circular economies [263–265] builds resilience in the water sector and also is on the right track for its sustainability [278]. There are however important divergences between resilience and sustainability in system thinking [271], because in order to deal with risks associated with change and uncertainty, a resilience approach relies more on the concept of adaptation, whereas a sustainability approach on that of transformation. Adaptation relates to decision making and actions to adjust to change, maintaining essential system functions (a more conservative approach), and on the contrary transformation implies reorganization and alteration of the system as the conditions become untenable (a more radical and pervasive approach) [112,271]. Within this context, Rees [279] categorizes three broad views on the nature of the necessary changes to achieve sustainable development regarding societal and political structures and human-environment relationship. These are the “status quo” - change can be achieved within the present structures, the “reform” - fundamental changes are necessary but without a full rupture with the current structures, and the “transformation” – radical changes are needed to the economic and power structures of society. Redman [271] views adaptation as an approach that citizens and elected officials are more comfortable with (as opposed to radical, uncertain in outcomes and costs, transformation), and thus resilience approaches are far more popular in the current political arena, as these tend towards the preservation of status quo [44,51,280]. Within this specific context, especially in the circles of social sciences interacting with the environment e.g., for urban resilience, disaster and crises management and climate change adaptation, there exists criticism for the term resilience and its operationalization. Many scholars (e.g., [43–45,63,281]) debate that resilience is a much-used (or even over-used) term in the political discourse, much like sustainability-motivated discourse in the past [282], and often disconnected from analytical concepts [283]. Thus, it is frequently critiqued whether it is a useful [65] or even an always positive concept [272,280,283,284]. As Anderies et al. [277] and Carpenter et al. [109] state, resilience as a system-wide property, is not normative, because it is not tied to specific performance measures that can always have a positive connotation (and both use the example of a dictatorship

establishment, that may constitute a resilient regime - as in enduring various changes and perturbations through time - but of course it is not a desirable state of government for the people). Matyas and Pelling [285] argue furthermore that resilience is a descriptive concept that can observe the system's stability but in order to determine if this stability is "good" or "bad", other analytical frameworks are necessary. However, for different stakeholders, normative judgements do emerge, concerning their particular interests. Thus, critique has been raised, that resilience, due to its all-encompassing broad nature, and the general lack of attentiveness to political power structures, scale and equity in societies, may allow interpretations of policies, decisions or actions that may promote a neoliberal agenda [286,287,284] and retain systemic inequalities (poverty, social injustice), as resilience-oriented. For systems that passively go through adaptive cycles even in a resilient manner, an unjust "status quo" may perpetuate, without addressing the actual causes of crises [288,289]. Thus, debating scholars in the aforementioned domains suggest concepts such as:

- Stakeholders structuring questions for operationalizing policies of resilience with the "five W's" [280]: for *whom* – potential trade-offs between stakeholders, *what* – which entity will be made resilient and for which threat, *when* – the temporal scale, *where* – the spatial scale, and *why* – understanding of the political context.
- "Negotiated resilience" [44], where resilience thinking is reframed as an active negotiation process between the different stakeholders and actors across different time and governmental scales, and not as a definitive goal set by a political agenda

Ultimately, while resilience had been in the past more outcome oriented, it shifted towards being more process-oriented [189,285], focusing on decision-making systems, and proactive practices instead of reactive. Presenting resilience as both a process and an outcome, can aid in lifting abstractions from policy agendas, and clarify objectives, pathways to achievement, and the involvement of or effects on relevant stakeholders.

Often in the systems' analysis literature, resilience is associated with, compared with, and distinguished from *risk* [42,235,290,291], as both terms appear together increasingly regularly in risk analysis and management studies. Risk itself is another term with a plethora of definitions and conceptualizations; Typically, risk has three determinants, i.e., hazard, exposure and vulnerability [42,292], and is commonly quantified as "a measure of the probability and severity of adverse effects" [293]. It can be computable, e.g., by employing the theory of scenario structuring (TSS) [294], by assigning likelihoods and consequences to scenarios. This premise, however, means that risk can always be characterized by a frequency distribution of events following known or measurable probabilities [295], e.g., from evidence-based data like historical records in what can be described as a *Knightian risk* [296]. However, there is an abundance of events without known or measurable distributions, and this level of ignorance about the future is called *Knightian uncertainty*. The uncertainties can be aleatory or epistemic in nature, meaning that they either represent a fundamentally complex or arbitrary behaviour, or our understanding of the phenomenon in question, and/or our modelling capacity and measurement accuracy are lacking (e.g., the future progress of climate change, the cyber-physical attacks that a CI may encounter) [15]. There are also unknowable [297] events, including the so called *Black Swans* [298], which are outside of the realm of regular expectations, producing extreme catastrophic impacts. Such uncertainties about the future cannot be reduced via collecting information and are not statistical in nature ([299,300]). This uncertainty-awareness in systems' design led to the adoption of the term *deep uncertainty* [301,300], for strategic planning cases where stakeholders cannot reach a consensus about models for system variables, the probability distributions for key parameters in order to represent uncertainty, and how to interpret the desirability of alternative outcomes. Contrary to risk, most often resilience is viewed as an

endowed system property that aids in absorbing, adapting or recovering from uncertain, unexpected shocks in an inevitably ever-changing world [42,92], rather than becoming highly adapted to specific threats [49]. In this context, resilience-oriented studies deal with how complex systems will interact openly as a whole entity to their environment, and acquire new emergent properties, resisting the wildly unknown perturbations that arise [257].

Many studies, especially in the field of natural disasters and hazards deal with resilience and *vulnerability* as interlinked concepts e.g. [63,65,113,120]. Vulnerability can broadly defined as the potential for loss [302] or the susceptibility to be harmed [113], but similarly to resilience can be defined in many different ways. In policy discourse and development planning in social, socio-ecological systems or socio-technical systems (e.g., urban environments, communities) resilience has been steadily replacing vulnerability [63], presumably on the basis of its positive connotation [45,281,303]; conversely, vulnerability in general has a negative nuance. The most-often conceptualized components of vulnerability in literature are the exposure to hazards (perturbations and/or external stresses), sensitivity to perturbation, and adaptive capacity [113,304]. However, for many scholars in the field of SES adaptive capacity is integral to resilience instead. As such, there are many different interpretations in the literature about the linkage of resilience and vulnerability. The interpretations range from resilience being the opposite of vulnerability [189,212,305,306], resilience being one of the components of vulnerability [307,194], resilience and vulnerability being two different inherent properties of the system [116,117,120,188,308], but linked, with some overlap between them. However, for the other key sub-components of vulnerability, i.e., exposure to hazards and sensitivity, there are multiple points of convergence between resilience and vulnerability, and these are the concepts that link these terms back to *risk* as well.

Generally, *hazards* are defined as threats to the system, comprised of perturbations and stress [194]. Perturbations are conceived as major spikes in pressure outside the normal range of systems variability, whereas stress as a continuous or increased pressure. There are many different views on the typology of pressures e.g., some taxonomize perturbations as exogenous to the system and stresses as endogenous [194], while others view all types of pressures as both feasibly endogenous or exogenous [4,12,188,309]. Butler et al. [4] categorizes threats in a universal way into four types on a two-axes system: internal/-external and acute/chronic. Sensitivity is broadly defined as the degree to which a system is modified or affected by perturbations [113], with various diverging contexts as well. For example, Smit and Wandel [304] argue that sensitivity and exposure are almost inseparable properties of a system and reflect the likelihood of the system experiencing particular conditions. On the other hand, Gallopín [310] argues that only sensitivity is an inherent ability of a system and contributes to vulnerability together with its capacity of response, whereas exposure is an attribute of the relation between the system and perturbation. It is also pointed out that a system could be very sensitive to a particular perturbation but be falsely considered non-vulnerable to the hazard if never being exposed to it. In that sense, including or excluding exposure to hazards as a component to determine vulnerability is a very important decision for the design of policies. A good CI example is the cyber-physical Stuxnet attack in the Natanz nuclear plant. As it turned out, the CPS was indeed sensitive and vulnerable to the hazard of cyber attacks, even though it was an air-gapped system, thought to be non-exposed to such hazards. The malware breached the system through the simple vector of an infected USB stick. In hindsight, the incident could have been avoided, if a better security – and thus resilience - policy was implemented within the facility, restricting access to external media. However, an interesting consensus in the literature is that exposures and sensitivities are rarely known a priori [304], circling back to the notion of unknown and unknowable hazards, i.e., the inevitable *deep uncertainty* enveloping complex systems, and thus again in the territory of resilience theory and analysis. In the sane manner, many recent studies employ a multi-hazard

approach (e.g., [311,312] in both the risk and the resilience assessment of systems, especially in CI systems due to their interdependencies, moving beyond traditional single and specific hazard assessments [142], with emphasis on generally strengthening resilience traits to tackle unknown threats.

Finally, the concept of *robustness* is also often associated with resilience in system analysis [277], due to its operationalization within studies of complex systems that endure future change [313]. Robustness, originating from the statistical analysis domain [95] and then transcending into the decision support fields for water resources is traditionally viewed as the insensitivity of a design to deviations (errors, random or not), from its original estimated design parameters [314]. Like resilience, numerous schemes for estimation exist, and a taxonomy of such methods can be found in the recent work of Herman et al. [313]. In the context of system analysis robustness is viewed as a desired property that describes an entity's ability to withstand a given level of stress without any degradation or loss of function [121]. This is a concept strongly correlated with resilience, in the sense that robustness allows a system to absorb shocks [315–317], therefore contributing to its resilience. An important distinction should be noted however: robustness can be clearly defined and identified, highlighting the extent to which a system can cope uncomplicatedly. On the other hand, resilience highlights a much different behaviour aspect, that of the system's under uncertain perturbations, that may force a system outside of its stable state, assessing its capacity to adapt to these changes and/or recover. Therefore, a very robust system is also resilient, but the opposite does not necessarily hold: a system can be resilient without being robust. An analogy of this robustness versus resilience principle can be found in Read [318], where the behaviour (displacement due to wind) of a palm tree under strong winds is contrasted to that of a sycamore tree. The latter can withstand heavy winds without noticeable trunk displacement, thus is robust, but may be uprooted abruptly – whereas the former bends easily and wildly but manages to eventually cope with even very heavy winds. Also, it should be noted, that as some scholars suggest (e.g., Homayounfar et al. [316]) trying to make a system very robust against some specific disturbances usually comes with the trade-off of increasing vulnerability to others (thus raising the question 'Is it really resilient?'). An example is in smart decentralized energy grids, where although the overall grid is less prone to large scale disruptions due to weather for example, it becomes more susceptible to CPAs [319]. There are also definitions of robustness that are related to resilience and both are assessed using the same methodology, as for example in Makropoulos et al. [41] and Nikolopoulos et al. [265,320]. As such, within the context of an engineering system in general, and CIs in particular, robustness would refer to the given level of stress absorbed before reaching a failure state, while resilience to the behaviour or performance under disturbances that include failure states. In other words, the concept comes back at the discussion of fail-safe systems versus safe-to-fail-systems, where the systems behaviour within a failure state or in general outside the design specifications is equally as important.

6. Directions for future research and advancements to CI applications

Taking into account the extended literature review elaborated and the wealth of scholarly work in the interdisciplinary topic of resilience, we focus on three emerging questions from the key academic, practice and policymaking standpoints. Subsequently we highlight the future directions from the perspective of the CI protection domain.

6.1. Does academia still need more literature on resilience?

The very steep rise in relevant literature publications in the recent years as seen in Fig. 1, may prompt an inquiry into whether there is still the need for scholars to devote time in resilience research. At least for

the foreseeable future, given the current trend, the increasing number of scholars involved with the subject matter, and the ongoing incorporation of resilience into policy mandates, academic literature will be enriched with even more works. On the one hand, there currently do not yet exist other thoroughly researched universal “policy contenders” as theoretical constructs with a similar positive connotation able to replace it. The closest candidate could be antifragility, which has recently gained traction, and describes the ability of a system to benefit, thrive, and grow when exposed to uncertainty and adversity [268]. However, most examples have been identified on organizational and financial systems that opportunistically change activities when under uncertain conditions to profit [321,267]. Fully adapting the principal to CIs is difficult because it implies that they can change roles and functions (contradicting with the notion of “critical”), and also scholars have expressed opinions that antifragility on urban systems like flood and water infrastructure is based on learning from past adversities and gradually adapting to them [16] – thus the principal significantly overlaps with the idea of ecological resilience and the adaptive cycle. On the other hand, resilience thinking will almost certainly continue to evolve correlated with the rapid rates of environmental, socioeconomic, political and institutional changes in the broader context of the future world, as well as with the transformation of CIs to smart cyber-physical systems and beyond. New concepts, technologies and practices will emerge in order to strengthen resilience, while their predecessors will be standardized into the design philosophy and language of systems, leading to even more research on the topic.

6.2. Will there ever be a common interpretation or quantification of resilience?

Resilience is an interdisciplinary concept and applicable to a multitude of different systems with unique characteristics and functions, roles and objectives of interest, which in turn produce distinct ways to measure or evaluate “performance”, “state” or the “effects of uncertainty”. As such there will always be nuances in the definition and terminology, even within the narrower socio-technical realm of CIs. There is however a clear transition to interpretations that relate to behaviour under uncertainties and failures maintaining critical functions as much as possible, as well as learning from them and adapt, which provides an adequate mental model to support strategic planning, design and operational management of CIs. What remains elusive is the operationalization through quantification as a metric. It has been suggested that resilience is best observed empirically “ex-post” [322,323], implying that a priori estimation is challenging. However, stress-testing CI systems through simulation schemes against an ensemble of extreme scenarios can allow the generation of evidence based results and metrics of the behaviour of systems [41]. Compound scenarios [255], i.e., with multiple stressors incorporated within a timeframe, and/or including short-term “wildcard” events [128,265] are especially useful for operationalization under deep uncertainty. It should be noted that in stress-testing the probability of such scenarios occurring is as irrelevant to the assessment, as it is impractical and impossible to quantify in the non-trivial cases, and almost certainly it is not the worst possible set of conditions that will affect a system. There will always be a subjective bias in a stress-testing procedure, and the highly complex and open-ended reality will always produce more hazards than what is imaginable. By shifting the focus on what “middle state” [4] or failure mode the system in question can end up, alleviates the impossible task of identifying all possible what-ifs that caused it, and allows focusing on ‘tipping points’ of internal parameters of the CI system and their combinations. In some cases, a generic failure mode can adequately describe the outcome of many different scenarios leading to it – even unknowable, and the assessment of resilience can not only be straightforward but also be turned into a design paradigm. An example is given on Nikolopoulos and Makropoulos [324] where a resilient sensor placement optimization algorithm to tackle water quality sensor failures, be it

due to deliberate actions or malfunctions, is discussed.

6.3. Can policy regulations and mandates reinforce resilience at CI sectors?

Regulations are imperative to set the context for engineers and decision makers, putting forward a set of guidelines and standards, enforcing compliance and incentivize anticipation, preparedness and learning. Recent examples of regulatory initiatives in EU include the NIS2 [325] and CER [326]. The NIS2 significantly expands the range of sectors and CI entities subject to cybersecurity requirements (e.g., including public communications, wastewater, manufacturing, and health services) addressing a lasting gap in practice, and imposes stricter risk management and incident reporting obligations, which help build sectoral knowledge. The CER Directive enforces an all-hazards approach to physical resilience, covering 11 essential CI sectors (energy, transport, banking, health, water, digital infrastructure, etc.) requiring EU member states to adopt national resilience strategies and conduct risk assessments at least every four years to identify critical entities. Under CER, critical entities must identify key risks, take measures to ensure continuity of essential services, and report disruptive incidents. Similarly in the US, the Presidential Policy Directive 21 [327], established a national policy to strengthen and maintain the security and resilience of critical infrastructure against man-made and natural physical and cyber threats, under an “all-hazards” approach, rather than focusing on specific hazards in isolation.

Such regulatory mandates are steps to the right direction as these formalize the requirement of specific actions from CI operators, set high-level goals, and aim to improve cross-sector coordination by a common risk and resilience picture. However, there is a possible implementation and conformity gap, as there is yet to exist a standardized framework to assess resilience in CIs [328]. Nonetheless, alongside regulations, there are international organizations developing standardized guidelines that can supplement the regulations, for example ISO 31000:2018 [329] for risk management and ISO 22301 [330] for business continuity and resilience. Such guidelines provide CI operators and decision makers tested and harmonized checklists and processes to follow, from how to conduct a risk assessment, to how to structure a continuity plan and test it regularly. In addition, international bodies are also active in the policy discourse, such as the United Nations Office for Disaster Risk Reduction (UNDRR) which recently published a set of principles for resilient infrastructure along a set of actions for each to be followed. Examples of actions are the adoption of open standards for information sharing for the shared responsibility principal, and conducting regular stress-testing of systems for the continuous learning principal [331]. Conforming with national regulations, and harmonization with international standards and best practises is a pragmatically difficult endeavour at the large scale. But, it can improve coherence in actions and risk management processes, and bolster cross-sectoral learning and lessons-learned sharing, which in the long run can mitigate occurrences of cascading effects between interconnected infrastructure.

6.4. Future steps towards CI resilience

In the face of impending CI disruptions due to climate change, natural disasters, cyber-physical attacks, and large-scale socioeconomical changes, resilience thinking can guide a) engineers to develop the necessary traits in the design, b) decision-makers to accept higher development costs in planning in order to strengthen sectoral resilience against uncertainties and understand the long-term benefits, and c) policy-makers to foster a supportive socio-technical, regulatory and legislative environment around them. These prepositions extend also to managing existing infrastructure; various past notions should be revisited under the context of resilience, especially ‘build and forget’ schemes which unfortunately are common for old infrastructure. CI sectors should embrace the learning and adaptation concepts interlinked with

resilience to restructure and repurpose systems. But to support this shift, several gaps should be bridged in the future, with the convergence of theoretical research and practice.

The first is the *technological* gap, as the field of CI protection, security and resilience needs the development of stress-testing modelling testbeds for all types of CIs against scenarios of compound hazards. Utilizing them and generating evidence-based results of behaviour under disruptions will build knowledge and understanding, and lead to the development of resilience measures and actions. Establishing common inter- and cross sectoral benchmarking methodologies will aid in harmonisation of the assessment frameworks. The scenarios developed for stress-testing to assess CI performance can also form contingency plans for operational management during crises, aiding in anticipation and preparedness. A recent example stemming from water CIs is the PROCRUSTES testbed for exploring resilience against cyber-physical attacks [332]. In addition, modelling of the interdependence of CI and the cascading effects from their failures presents another technological gap [333]. This is due to the challenges of capturing all types of dependencies in their complex behaviour and different dynamics (effects of time), as interconnected CIs are essentially a *system-of-systems* [334]. It is an active research area with various approaches of modelling that ranged from network-based (CI topology or service flow methods) (e.g., [335]), bottom-up agent based modelling with agents representing operators, facilities, or whole networks (e.g., [336]), system dynamics modelling feedback loops and time-delays between CIs (e.g., [337]), as well as co-simulation of multiple CIs [338]. Recent promising advances (e.g., [237,339,340]) use the open high level architecture (HLA) standard [341] for complex distributed simulation (federations), and can manage data exchange and synchronization of heterogeneous models and simulation tools at different levels, producing high fidelity results. The main advantage is the possibility to couple already developed and benchmarked tools such as CI-specific stress-testing testbeds for a detailed low level that simulates sub-systems, and use them as inputs to a higher level representing the interconnectivity of the system [342]. Incorporating these exploratory simulation tools in digital twins [343] of infrastructure at regional or national level capitalize on real-time monitored data, providing early warning capabilities [331].

Another issue is the *resources and capacity* gap, especially among smaller or less mature CI operators, in order to conform with regulations and guidelines and strengthen their systems' resilience. For example, small water utilities or regional hospitals may lack specialized cybersecurity staff or the funds to implement advanced resilience measures. Solving this problem will require the formation of national institutions responsible for overseeing the required processes and providing the necessary funds and expert personnel. On a similar note, global threats like climate change and transnational cybercrime, can only be effectively addressed by international co-operation, and formal treaties, which due to geopolitical shifts will remain challenging.

Besides the aforementioned technological and economic gaps, there are the *knowledge* and *awareness* gaps that should be addressed to enhance community resilience. A continuous trusted learning process is essential for both the CI organizations and the communities served [344]. This encompasses a) the systematic and open dissemination of hazard and contingency planning information by CI organizations (e.g., by using standardized databases and ensuring accurate and timely reporting of CI disruptions [345]), and b) structured CI and community training in emergency management and preparedness. Knowledge sharing becomes very important in awareness, as studies have shown that CI operators are more aware for their dependencies than those they generate [346]. Institutionalized and real-time public-private intelligence sharing should shorten detection timelines of threats and prevent cascading failures [347]. These efforts also aid in shortening the *participation* gap, as it involves all the relevant stakeholders [344,345] in the process of understanding risks and uncertainties, supported by learning and clarifying shared responsibilities.

As a final point, these gaps should be promptly considered under a

national security, defence and preparedness lens for the possibility of future conflicts as the geopolitical environment is increasingly volatile. Both past and recent wars demonstrate that CIs are the prime attack targets to degrade the ability of a state to sustain key military activities, because the civil-military cooperation is the critical link between preparedness ambitions and operational delivery [348]. The Ukrainian conflict exemplifies the compounding effect of multiple threat vectors to civil CIs used as a strategic instrument, like the cyber attacks along with physical attacks to the power grid to incapacitate it [349], and the destruction of the Kakhlova Dam amidst a period when it had reached a 30-year high water level [350]; the same conflict also demonstrates how to achieve resilience in the power grid by closing the gaps, i.e. through hybrid architectures with manual analog redundancy along digitalized control and monitoring systems, mandatory security protocols, an inter-institutional dedicated incident response unit, scenario modelling and stress-testing, and technological improvisations especially in modernizing communications and decentralization of assets [347,349].

Thus, for CI resilience to move beyond a policy mandate in the regulatory texts, a) an uncertainty-aware culture should be cultivated in the CI sectors and the communities, fostered through governmental, educational, training, and standardization institutions, and b) the applied research domain should develop in conjunction methodologies, tools, and procedures for CI resilience assessment and their interdependencies. These are the most important aspects that should be highlighted, communicated and guided from policy makers and inter-governmental institutions.

7. Concluding remarks

The world changes rapidly, and the critical infrastructure that sustains human society and welfare will inevitably face unprecedented challenges. Policy and regulatory bodies call for strengthening systems' resilience; however, the analysis shows that with the ever-increasing body of literature in diverging fields, it is difficult to establish a common interpretation and quantification method. Nonetheless, as an interdisciplinary term, through osmosis, evolution and exposure to policy contexts, resilience thinking has encompassed a set of properties, applicable to all phases of planning, development and operation of CIs, advocating for an environment of safety, security, and contingency planning. CI sectors are in dire need of a shift to systems that are uncertainty-aware, developed with inherent traits to avoid catastrophic failures while still retaining a level of function. A research-practice-society nexus that anticipates disruptions, models and stress-tests systems to identify weak points and limitations, learns from events, shares knowledge and adapts to change, is imperative to practically incorporate resilience as an intrinsic characteristic of future CIs.

CRedit authorship contribution statement

Dionysios Nikolopoulos: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christos Makropoulos:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

References

- [1] C.S. Holling, Resilience and stability of ecological systems, *Annu. Rev. Ecol. Syst.* 4 (1) (1973) 1–23.
- [2] E.Z. Stakhiv, Pragmatic approaches for water management under Climate change Uncertainty, *JAWRA J. Am. Water Resour. Assoc.* 47 (6) (2011) 1183–1196.
- [3] J. Ahern, From fail-safe to safe-to-fail: sustainability and resilience in the new urban world, *Landsc. Urban Plan.* Elsevier B.V. 100 (4) (2011) 341–343.
- [4] D. Butler, S. Ward, C. Sweetapple, M. Astaraie-Imani, K. Dia, R. Farmani, G. Fu, Reliable, resilient and sustainable water management: the Safe & SuRe approach, *Glob. Chall.* 1 (1) (2017) 63–77.
- [5] S.M. Fletcher, M. Miotto, J. Swaminathan, M.M. Klemun, K. Strzepek, A. Siddiqi, Water Supply infrastructure planning: decision-making framework to classify multiple uncertainties and evaluate flexible design, *J. Water Resour. Plan. Manag.* 143 (10) (2017) 04017061.
- [6] M. Reynolds, To stop London running out of water, a crack squad is hunting down the city's mega leaks, *WIRED* (2019). <, <https://www.wired.co.uk/article/london-thames-water-leaks>. >(Nov. 17, 2022).
- [7] R. Brown, R. Ashley, M. Farrelly, Political and professional agency entrapment: an agenda for Urban Water research, *Water Resour. Manag.* 25 (15) (2011) 4037–4050.
- [8] M. Farrelly, R. Brown, Rethinking urban water management: experimentation as a way forward? *Glob. Environ. Change Elsevier Ltd* 21 (2) (2011) 721–732.
- [9] F.W. Geels, From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory, *Res. Policy* 33 (6–7) (2004) 897–920.
- [10] F.J. de Haan, B.C. Rogers, N. Frantzeskaki, R.R. Brown, Transitions through a lens of urban water, *Environ. Innov. Soc. Transit.* 15 (2015) 1–10.
- [11] R.M. Clark, S. Hakim, A. Ostfeld, in: R.M. Clark, S. Hakim, A. Ostfeld (Eds.), *Handbook of Water and Wastewater Systems Protection*, Springer New York, New York, NY, 2011.
- [12] T.P. Dawson, M.D.A. Rounsevell, T. Klůváňková-Oravská, V. Chobotová, A. Stirling, Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision, *Biodivers. Conserv.* 19 (10) (2010) 2843–2853.
- [13] P. Juan-García, D. Butler, J. Comas, G. Darch, C. Sweetapple, A. Thornton, L. Corominas, Resilience theory incorporated into urban wastewater systems management. State of the art, *Water Res.* Elsevier Ltd 115 (2017) 149–161.
- [14] S. Ramphal, Advance the New Normal, exploring water-energy-waste partnerships, IWA (2018). <http://www.iwa-network.org/advance-the-new-normal-exploring-water-energy-waste-partnerships/> (Nov. 1, 2018).
- [15] S. Hallegatte, A. Shah, R. Lempert, C. Brown, S. Gill, *Investment Decision Making Under Deep Uncertainty - Application to Climate Change*. Policy Research Working Papers, The World Bank, 2012.
- [16] F. Babovic, V. Babovic, A. Mijic, Antifragility and the development of urban water infrastructure, *Int. J. Water Resour. Dev.* 34 (4) (2018) 499–509.
- [17] P.C.D. Milly, J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D. P. Lettenmaier, R.J. Stouffer, Stationarity is dead: whither water management? *Science* 319 (5863) (2008) 573–574.
- [18] R.J. Dawson, D. Thompson, D. Johns, R. Wood, G. Darch, L. Chapman, P. N. Hughes, G.V.R. Watson, K. Paulson, S. Bell, S.N. Gosling, W. Powrie, J.W. Hall, A systems framework for national assessment of climate risks to infrastructure, *Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci.* 376 (2121) (2018) 20170298.
- [19] M. Falkenmark, J. Rockström, Building water resilience in the face of global change: from a blue-only to a green-blue water approach to land-water management, *J. Water Resour. Plan. Manag.* 136 (6) (2010) 606–610.
- [20] W.J. Cosgrove, D.P. Loucks, Water management: current and future challenges and research directions, *Water Resour. Res.* 51 (6) (2015) 4823–4839.
- [21] A. Efstratiadis, G.-K. Sakki, Revisiting the management of water-Energy systems under the umbrella of resilience optimization. EWaS5 International Conference: “Water Security and Safety Management: Emerging Threats Or New Challenges? Moving from Therapy and Restoration to Prognosis and Prevention”, MDPI, Basel Switzerland, 2022, p. 72.
- [22] R. Rajkumar, (Raj), I. Lee, L. Sha, J. Stankovic, Cyber-physical systems: the next computing revolution, *Cybern. Syst. Anal.* IEEE 53 (6) (2017) 821–834.
- [23] E. Lee, The past, present and future of cyber-physical systems: a focus on models, *Sensors* 15 (3) (2015) 4837–4869.
- [24] E.A. Lee, Cyber physical systems: design challenges, in: *2008 11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC)*, IEEE, 2008, pp. 363–369.
- [25] E. Sisinni, A. Saifullah, S. Han, U. Jennehag, M. Gidlund, Industrial Internet of Things: challenges, opportunities, and directions, *IEEE Trans. Ind. Inform.* IEEE 14 (11) (2018) 4724–4734.
- [26] Geng Wu, S. Talwar, K. Johnsson, N. Himayat, K.D. Johnson, M2M: from mobile to embedded internet, *IEEE Commun. Mag.* 49 (4) (2011) 36–43.
- [27] M. Chen, S. Mao, Y. Liu, Big Data: a survey, *Mob. Netw. Appl.* 19 (2) (2014) 171–209.
- [28] R. Buyya, C.S. Yeo, S. Venugopal, J. Broberg, I. Brandic, Cloud computing and emerging IT platforms: vision, hype, and reality for delivering computing as the 5th utility, *Future Gener. Comput. Syst.* Elsevier B.V. 25 (6) (2009) 599–616.
- [29] M. Chiang, T. Zhang, Fog and IoT: an overview of research opportunities, *IEEE Internet Things J.* 3 (6) (2016) 854–864.
- [30] R. Bogue, Towards the trillion sensors market, *Sens. Rev.* 34 (2) (2014) 137–142.
- [31] J.G. Andrews, S. Buzzi, W. Choi, S.V. Hanly, A. Lozano, A.C.K. Soong, J.C. Zhang, What will 5G Be? *IEEE J. Sel. Areas Commun.* 32 (6) (2014) 1065–1082.

- [32] Y. Lu, Industry 4.0: a survey on technologies, applications and open research issues, *J. Ind. Inf. Integr.* Elsevier Inc 6 (2017) 1–10.
- [33] A. Rasekh, A. Hassanzadeh, S. Mulchandani, S. Modi, M.K. Banks, Smart water networks and cyber security, *J. Water Resour. Plan. Manag.* 142 (7) (2016) 01816004.
- [34] G. Loukas, A cyber-physical world. *Cyber-Physical Attacks*, Butterworth-Heinemann (Elsevier), Oxford, UK, 2015, pp. 1–19.
- [35] D.E. Denning, Stuxnet: what has changed? *Future Internet* 4 (3) (2012) 672–687.
- [36] A. Nicholson, S. Webber, S. Dyer, T. Patel, H. Janicke, SCADA security in the light of cyber-warfare, *Comput. Secur. Elsevier Ltd* 31 (4) (2012) 418–436.
- [37] M. Mesbah, M. Azer, Cyber threats and policies for industrial control systems, in: *2019 International Conference on Smart Applications, Communications and Networking (SmartNets)*, IEEE, 2019, pp. 1–6.
- [38] J. Slay, M. Miller, Lessons learned from the Maroochy water breach. *Critical Infrastructure Protection*, Springer US, Boston, MA, 2007, pp. 73–82.
- [39] C. Pahl-Wostl, P. Jeffrey, N. Isendahl, M. Brugnach, Maturing the new water management paradigm: progressing from aspiration to practice, *Water Resour. Manag.* 25 (3) (2011) 837–856.
- [40] C.S. Holling, Engineering resilience versus ecological resilience, in: P. Schulze (Ed.), *Engineering Within Ecological Constraints*, National Academy Press, Washington, DC, 1996, pp. 31–43.
- [41] C. Makropoulos, D. Nikolopoulos, L. Palmen, S. Kools, A. Segrave, D. Vries, S. Koop, H.J. van Alphen, E. Vonk, P. van Thienen, E. Rozos, G. Medema, A resilience assessment method for urban water systems, *Urban Water J. Taylor Fr.* 15 (4) (2018) 316–328.
- [42] R. Francis, B. Bekera, A metric and frameworks for resilience analysis of engineered and infrastructure systems, *Reliab. Eng. Syst. Saf. Elsevier* 121 (2014) 90–103.
- [43] S. Davoudi, K. Shaw, L.J. Haider, A.E. Quinlan, G.D. Peterson, C. Wilkinson, H. Fünfgeld, D. McEvoy, L. Porter, S. Davoudi, Resilience: a bridging concept or a dead end? ‘reframing’ Resilience: challenges for planning theory and practice interacting traps: resilience assessment of a pasture management system in Northern Afghanistan urban Resilience: what does it mean in Planni, *Plan. Theory Pract.* 13 (2) (2012) 299–333.
- [44] L.M. Harris, E.K. Chu, G. Ziervogel, Negotiated resilience, *Resilience* 3293 (July) (2017) 1–19.
- [45] K. Shaw, L. Maythorne, Managing for local resilience: towards a strategic approach, *Public Policy Adm.* 28 (1) (2013) 43–65.
- [46] K. Brown, Resilience, Development and Global Change, Routledge, Oxon, UK, 2015.
- [47] S. Bueno, V.A. Bañuls, M.D. Gallego, Is urban resilience a phenomenon on the rise? A systematic literature review for the years 2019 and 2020 using textometry, *Int. J. Disaster Risk Reduct.* (2021) 66.
- [48] E. Lawson, R. Farmani, E. Woodley, D. Butler, A resilient and sustainable water sector: barriers to the operationalisation of resilience, *Sustainability* 12 (5) (2020) 1797.
- [49] S. Meerow, J.P. Newell, M. Stults, Defining urban resilience: a review, *Landsc. Urban Plan. Elsevier B.V* 147 (2016) 38–49.
- [50] L. Xu, D. Marinova, Resilience thinking: a bibliometric analysis of socio-ecological research, *Scientometrics* 96 (3) (2013) 911–927.
- [51] J. Walker, M. Cooper, Genealogies of resilience, *Secur. Dialogue* 42 (2) (2011) 143–160.
- [52] S.L. Star, The structure of ill-structured solutions: boundary objects and heterogeneous distributed problem solving, *Distrib. Artif. Intell.* (1989).
- [53] S.C. van Pelt, M. Haasnoot, B. Arts, F. Ludwig, R. Swart, R. Biesbroek, Communicating climate (change) uncertainties: simulation games as boundary objects, *Environ. Sci. Policy Elsevier Ltd* 45 (2015) 41–52.
- [54] J.A. Baggio, K. Brown, D. Hellebrandt, Boundary object or bridging concept? A citation network analysis of resilience, *Ecol. Soc. Elsevier* 20 (2) (2015) art2.
- [55] S. Deppisch, S. Hasibovic, Social-ecological resilience thinking as a bridging concept in transdisciplinary research on climate-change adaptation, *Nat. Hazards* 67 (1) (2013) 117–127.
- [56] L.H. Gunderson, Ecological resilience—In theory and application, *Annu. Rev. Ecol. Syst.* 31 (1) (2000) 425–439.
- [57] B. Pizzo, Problematising resilience: implications for planning theory and practice, *Cities Elsevier Ltd.* 43 (2015) 133–140.
- [58] L.J. Vale, The politics of resilient cities: whose resilience and whose city? *Build. Res. Inf.* 42 (2) (2014) 191–201.
- [59] Watson, J., Guttromson, R., Silva-monroy, C., Jeffers, R., Ellison, J., Rath, C., Gearhart, J., Jones, D., Corbet, T., and Walker, L.T. (2015). *Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States*. Sandia National Laboratories, Albuquerque, New Mexico, USA.
- [60] Cabinet Office. (2022). “The UK government resilience framework.” UK Government, <<https://www.gov.uk/government/publications/the-uk-government-resilience-framework/the-uk-government-resilience-framework.html>>(Aug. 21, 2023).
- [61] P. Hammond, We need to rethink resilience, *Spiked* (2014). <, <https://www.spiked-online.com/2014/10/10/we-need-to-rethink-resilience/>>. (Feb. 14, 2023).
- [62] S. Schwarz, Resilience in psychology: a critical analysis of the concept, *Theory Psychol.* 28 (4) (2018) 528–541.
- [63] J. Weichselgartner, I. Kelman, Geographies of resilience, *Prog. Hum. Geogr.* 39 (3) (2015) 249–267.
- [64] D.E. Alexander, Resilience and disaster risk reduction: an etymological journey, *Nat. Hazards Earth Syst. Sci.* 13 (11) (2013) 2707–2716.
- [65] R.J.T. Klein, R.J. Nicholls, F. Thomalla, Resilience to natural hazards: how useful is this concept? *Environ. Hazards* 5 (1) (2003) 35–45.
- [66] C. Bailey, Lucretius: on the Nature of Things. Translated by Cyril Bailey, Clarendon Press, Oxford, UK, 1910.
- [67] T. Tredgold, XXXVII. On the transverse strength and resilience of timber, *Philos. Mag.* 51 (239) (1818) 214–216.
- [68] Mallet, R. (1856). *On the Physical Conditions Involved in the Construction of Artillery: an Investigation of the Relative and Absolute Values of the Materials Principally Employed and of Some Hitherto Unexplained Causes of the Destruction of the Canon in Service*. Longmans, Brown, Green, Longmans, and Roberts, London, UK.
- [69] G. Ferrari, A. McConnell, Robert Mallet and the ‘great neapolitan earthquake’ of 1857, *Notes Rec. R. Soc.* 59 (1) (2005) 45–64.
- [70] R. Mallet, The First Principles of Observational Seismology As Developed in the Report to the Royal Society of London to Investigate the Circumstances of the Great Earthquake of December 1857, Chapman and Hall, London, UK, 1862.
- [71] W. Fairbairn, Treaties On Iron Ship Building: Its History and Progress as Comprised in a Series of Experimental Researches On the Laws of Strain, Longmans, Green & co, London, UK, 1865.
- [72] M. Merriman, A Text-book on the Mechanics of Materials and of Beams, Columns and Shafts, First Edition. New York: J. Wiley and Sons, John Wiley and Sons, New York, NY, USA, 1885.
- [73] R.H. Thurston, On the strength, elasticity, ductility and resilience of materials of machine construction, *J. Frankl. Inst.* 97 (5) (1874) 344–356.
- [74] J. Gordon, Structures, Penguin Books, Harmondsworth, UK, 1978.
- [75] J. Gere, B. Goodno, Mechanics of Materials, Cengage Learning, Toronto, Canada, 2009.
- [76] A. McAslan, The Concept Of Resilience: Understanding its Origins, Meaning and Utility, Torrens Resilience Institute, Adelaide, Australia, 2010.
- [77] D.A. Bloch, E. Silber, S.E. Perry, Some factors in the emotional reaction of children to disaster, *Am. J. Psychiatry* 113 (5) (1956) 416–422.
- [78] A.D.B.M. Clarke, A.D.B.M. Clarke, S. Reiman, Cognitive and social changes in the feeble-minded-three further studies, *Br. J. Psychol.* 49 (2) (1958) 144–157.
- [79] N. Garnezy, Vulnerability research and the issue of primary prevention, *Am. J. Orthopsychiatry* 41 (1) (1971) 101–116.
- [80] J. Kagan, Resilience in cognitive development, *Ethos* 3 (2) (1975) 231–247.
- [81] A.S. Masten, K.M. Best, N. Garnezy, Resilience and development: contributions from the study of children who overcome adversity, *Dev. Psychopathol.* 2 (4) (1990) 425–444.
- [82] M. Rutter, Resilience in the face of adversity, *Br. J. Psychiatry* 147 (6) (1985) 598–611.
- [83] M. Rutter, Resilience: some conceptual considerations, *J. Adolesc. Health* 14 (8) (1993) 626–631.
- [84] G.A. Bonanno, Loss, trauma, and Human resilience: have we underestimated the Human capacity to thrive after extremely aversive events? *Am. Psychol.* 59 (1) (2004) 20–28.
- [85] B. Egeland, E. Carlson, L.A. Sroufe, Resilience as process, *Dev. Psychopathol.* 5 (4) (1993) 517–528.
- [86] S.S. Luthar, D. Cicchetti, B. Becker, The construct of resilience: a critical evaluation and guidelines for future work, *Child Dev.* 71 (3) (2000) 543–562.
- [87] H.B. Kaplan, Toward an understanding of resilience: a critical review of definitions and models, in: M.D. Glantz, J.L. Johnson (Eds.), *Resilience and Development*, Kluwer Academic, New York, NY, 1999, pp. 17–83.
- [88] G.W. Lasker, Human Biological adaptability, *Science* 166 (3912) (1969) 1480–1486.
- [89] F.H. Norris, S.P. Stevens, B. Pfefferbaum, K.F. Wyche, R.L. Pfefferbaum, Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness, *Am. J. Community Psychol.* 41 (1–2) (2008) 127–150.
- [90] S.T.A. Pickett, M.L. Cadenasso, J.M. Grove, Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms, *Landsc. Urban Plan.* 69 (4) (2004) 369–384.
- [91] C. Folke, Resilience: the emergence of a perspective for social–ecological systems analyses, *Glob. Environ. Change* 16 (3) (2006) 253–267.
- [92] S. Meerow, J.P. Newell, Resilience and complexity: a bibliometric review and prospects for industrial ecology, *J. Ind. Ecol.* 19 (2) (2015) 236–251.
- [93] F.E. Clements, Nature and structure of the climax, *J. Ecol.* 24 (1) (1936) 252.
- [94] M.B. Fiering, C.S. Holling, Management and standards for perturbed ecosystems, *Agro-Ecosyst.* 1 (1973) (1974) 301–321.
- [95] M. Fiering, The role of systems analysis in water program development, *Nat. Resour. J.* 16 (4) (1976) 25–37.
- [96] R.V. O’Neil, D.I. DeAngelis, J.B. Waide, T.F.H. Allen, in: R. May (Ed.), *A Hierarchical Concept of Ecosystems*, Princeton University Press, Princeton, New York, 1994.
- [97] S.L. Pimm, The complexity and stability of ecosystems, *Nature* 307 (5949) (1984) 321–326.
- [98] S.L. Pimm, The Balance of nature: Ecological Issues in the Conservation of Species and Communities, University of Chicago Press, Chicago, Usa, 1991.
- [99] D. Tilman, J.A. Downing, Biodiversity and stability in grasslands, *Nature* 367 (6461) (1994) 363–365.
- [100] T. Hashimoto, J.R. Stedinger, D.P. Loucks, Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation, *Water Resour. Res.* 18 (1) (1982) 14–20.
- [101] C.S. Holling, G.K. Meffe, Command and control and the pathology of natural resource management, *Conserv. Biol.* 10 (2) (1996) 328–337.
- [102] B.H. Walker, D. Ludwig, C.S. Holling, R.M. Peterman, Stability of semi-arid Savanna Grazing systems, *J. Ecol.* 69 (2) (1981) 473.

- [103] B. Walker, C.S. Holling, S.R. Carpenter, A.P. Kinzig, Resilience, adaptability and transformability in social-ecological systems, *Ecol. Soc.* 9 (2) (2004) art5.
- [104] C. Folke, S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, C. S. Holling, Regime shifts, resilience, and biodiversity in ecosystem management, *Annu. Rev. Ecol. Evol. Syst.* 35 (2004) 557–581.
- [105] K.-H. Liao, A theory on urban resilience to floods—a basis for alternative planning practices, *Ecol. Soc.* 17 (4) (2012) art48.
- [106] M. Schlüter, C. Pahl-Wostl, Mechanisms of resilience in common-pool resource Management systems: an agent-based model of water use in a river basin, *Ecol. Soc.* 12 (2) (2007) art4.
- [107] F. Westley, P. Olsson, C. Folke, T. Homer-Dixon, H. Vredenburg, D. Looibach, J. Thompson, M. Nilsson, E. Lambin, J. Sendzimir, B. Banerjee, V. Galaz, S. van der Leeuw, Tipping toward sustainability: emerging pathways of transformation, *AMBIO* 40 (7) (2011) 762–780.
- [108] G.C. Gallopín, Human dimensions of global change: linking the global and the local processes, *Int. Soc. Sci. J.* 130 (4) (1991) 707–718.
- [109] S. Carpenter, B. Walker, J.M. Anderies, N. Abel, From metaphor to measurement: resilience of what to what? *Ecosystems* 4 (8) (2001) 765–781.
- [110] L.H. Gunderson, C.S. Holling, *Panarchy: Understanding Transformations in Human and Natural Systems*, Island press, Washington, D.C., 2001.
- [111] L.H. Gunderson, C.S. Holling, S.S. Light, *Barriers and Bridges to the Renewal of Ecosystems and Institutions*, Columbia University Press, New York, NY, USA, 1995.
- [112] D.R. Nelson, W.N. Adger, K. Brown, Adaptation to environmental change: contributions of a resilience framework, *Annu. Rev. Environ. Resour.* 32 (1) (2007) 395–419.
- [113] W.N. Adger, Vulnerability, *Glob. Environ. Change* 16 (3) (2006) 268–281.
- [114] T.H.F. Wong, R.R. Brown, The water sensitive city: principles for practice, *Water Sci. Technol.* 60 (3) (2009) 673–682.
- [115] L.K. Comfort, N. Oh, G. Ertan, S. Scheinert, Designing adaptive systems for disaster mitigation and response the role of structure, in: L.K. Comfort, A. Boin, C. K. Demchak (Eds.), *Designing Resilience: Preparing For Extreme Events*, University of Pittsburgh Press, Pittsburgh, PA, 2010, pp. 33–61.
- [116] S.L. Cutter, K.D. Ash, C.T. Emrich, The geographies of community disaster resilience, *Glob. Environ. Change Elsevier Ltd* 29 (2014) 65–77.
- [117] S.L. Cutter, L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, J. Webb, A place-based model for understanding community resilience to natural disasters, *Glob. Environ. Change* 18 (4) (2008) 598–606.
- [118] T.G. Frazier, C.M. Thompson, R.J. Dezzani, D. Butsick, Spatial and temporal quantification of resilience at the community scale, *Appl. Geogr. Elsevier Ltd* 42 (2013) 95–107.
- [119] D. Mileti, *Disasters By Design: A Reassessment of Natural Hazards in the United States*, Joseph Henry Press, Washington, D.C., 1999.
- [120] H. Zhou, J. Wang, J. Wan, H. Jia, Resilience to natural hazards: a geographic perspective, *Nat. Hazards* 53 (1) (2010) 21–41.
- [121] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities, *Earthq. Spectra* 19 (4) (2003) 733–752.
- [122] L.K. Comfort, *Shared Risk: Complex Systems in Seismic Response*, Emerald Group Publishing Limited, 1999.
- [123] T. McPhearson, E. Andersson, T. Elmqvist, N. Frantzeskaki, Resilience of and through urban ecosystem services, *Ecosyst. Serv. Elsevier* 12 (2015) 152–156.
- [124] C. Wilkinson, Social-ecological resilience: insights and issues for planning theory, *Plan. Theory* 11 (2) (2012) 148–169.
- [125] D.R. Godschalk, Urban hazard mitigation: creating resilient cities, *Nat. Hazards Rev.* 4 (3) (2003) 136–143.
- [126] R. Leichenko, Climate change and urban resilience, *Curr. Opin. Environ. Sustain.* 3 (3) (2011) 164–168.
- [127] S. Tyler, M. Moench, A framework for urban climate resilience, *Clim. Dev.* 4 (4) (2012) 311–326.
- [128] J.A. Wardekker, A. de Jong, J.M. Knoop, J.P. van der Sluijs, Operationalising a resilience approach to adapting an urban delta to uncertain climate changes, *Technol. Forecast. Soc. Change Elsevier Inc* 77 (6) (2010) 987–998.
- [129] D. Brunsden, A critical assessment of the sensitivity concept in geomorphology, *CATENA* 42 (2–4) (2001) 99–123.
- [130] D.P. Garrity, F.K. Akinnifesi, O.C. Ajayi, S.G. Weldesemayat, J.G. Mowo, A. Kalinganire, M. Larwanou, J. Bayala, *Evergreen Agriculture: a robust approach to sustainable food security in Africa*, *Food Secur.* 2 (3) (2010) 197–214.
- [131] L.J. Gordon, C.M. Finlayson, M. Falkenmark, Managing water in agriculture for food production and other ecosystem services, *Agric. Water Manag.* 97 (4) (2010) 512–519.
- [132] J. Pretty, Agricultural sustainability: concepts, principles and evidence, *Philos. Trans. R. Soc. B: Biol. Sci.* 363 (1491) (2008) 447–465.
- [133] J. Pretty, Z.P. Bharucha, Sustainable intensification in agricultural systems, *Ann. Bot.* 114 (8) (2014) 1571–1596.
- [134] T. Tschamtké, A.M. Klein, A. Krüess, I. Steffan-Dewenter, C. Thies, Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management, *Ecol. Lett.* 8 (8) (2005) 857–874.
- [135] F. Lloret, E.G. Keeling, A. Sala, Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests, *Oikos* 120 (12) (2011) 1909–1920.
- [136] H. Pretzsch, G. Schütze, E. Uhl, Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by inter-specific facilitation, *Plant Biol.* 15 (3) (2013) 483–495.
- [137] E.D. Vugrin, D.E. Warren, M.A. Ehlen, R.C. Camphouse, A framework for assessing the resilience of infrastructure and economic systems. *Sustainable and Resilient Critical Infrastructure Systems*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010, pp. 77–116.
- [138] B. Cai, M. Xie, Y. Liu, Y. Liu, Q. Feng, Availability-based engineering resilience metric and its corresponding evaluation methodology, *Reliab. Eng. Syst. Saf. Elsevier Ltd* 172 (2018) 216–224.
- [139] R. Farmani, G.A. Walters, D.A. Savic, Trade-off between total cost and reliability for Anytown Water Distribution Network, *J. Water Resour. Plan. Manag.* 131 (3) (2005) 161–171.
- [140] E. Todini, Looped water distribution networks design using a resilience index based heuristic approach, *Urban Water* 2 (2) (2000) 115–122.
- [141] A. Yazdani, R.A. Otoo, P. Jeffrey, Resilience enhancing expansion strategies for water distribution systems: a network theory approach, *Environ. Model. Softw. Elsevier Ltd* 26 (12) (2011) 1574–1582.
- [142] B.D. Trump, S.-A. Mitoulis, S. Argyroudis, G. Kiker, J. Palma-Oliveira, R. Horton, G. Pescaroli, E. Pinigina, J. Trump, I. Linkov, Threat-agnostic resilience: framing and applications, *Int. J. Disaster Risk Reduct.* 124 (2025) 105535.
- [143] J. Gao, B. Barzel, A.-L. Barabási, Universal resilience patterns in complex networks, *Nat. Nat. Publ. Group* 530 (7590) (2016) 307–312.
- [144] M. Panteli, P. Mancarella, The grid: stronger, bigger, smarter?: presenting a conceptual framework of power system resilience, *IEEE Power Energy Mag.* 13 (3) (2015) 58–66.
- [145] C. Shao, M. Shahidepour, X. Wang, X. Wang, B. Wang, Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience, *IEEE Trans. Power Syst.* 32 (6) (2017) 4418–4429.
- [146] C. Chen, J. Wang, F. Qiu, D. Zhao, Resilient distribution system by microgrids formation after natural disasters, *IEEE Trans. Smart Grid* 7 (2) (2016) 958–966.
- [147] A. Gholami, F. Aminifar, M. Shahidepour, Front lines against the darkness: enhancing the resilience of the electricity grid through microgrid facilities, *IEEE Electr. Mag.* 4 (1) (2016) 18–24.
- [148] R. Kinney, P. Crucitti, R. Albert, V. Latora, Modeling cascading failures in the North American power grid, *Eur. Phys. J. B* 46 (1) (2005) 101–107.
- [149] S. Lei, C. Chen, H. Zhou, Y. Hou, Routing and scheduling of mobile power sources for distribution system resilience enhancement, *IEEE Trans. Smart Grid IEEE* 10 (5) (2019) 5650–5662.
- [150] B.K. Sovacool, I. Mukherjee, Conceptualizing and measuring energy security: a synthesized approach, *Energy Elsevier Ltd* 36 (8) (2011) 5343–5355.
- [151] D.S. Callaway, M.E.J. Newman, S.H. Strogatz, D.J. Watts, Network robustness and fragility: percolation on random graphs, *Phys. Rev. Lett.* 85 (25) (2000) 5468–5471.
- [152] R. Cohen, K. Erez, D. Ben-Avraham, S. Havlin, Resilience of the internet to random breakdowns, *Phys. Rev. Lett.* 85 (21) (2000) 4626–4628.
- [153] Q. Zhu, T. Başar, Game-theoretic methods for robustness, security, and resilience of cyberphysical control systems: games-in-games principle for optimal cross-layer resilient control systems, *IEEE Control Syst.* 35 (1) (2015) 46–65.
- [154] R. Bhamra, S. Dani, K. Burnard, Resilience: the concept, a literature review and future directions, *Int. J. Prod. Res.* 49 (18) (2011) 5375–5393.
- [155] J. Fiksel, Sustainability and resilience: toward a systems approach, *Sustain.: Sci. Pract. Policy* 2 (2) (2006) 14–21.
- [156] J. Fiksel, M. Polyviou, K.L. Croxton, T.J. Pettit, From risk to resilience: learning to deal with disruption, *MIT Sloan Manag. Rev.* 56 (2) (2015) 79–86.
- [157] G. Hamel, L. Välikangas, The Quest for Resilience, *Harv. Bus. Rev.* 81 (9) (2003) 1–24.
- [158] J.F. Home, J.E. Orr, Assessing behaviors that create resilient organizations, *Employ. Relat. Today* 24 (4) (1997) 29–39.
- [159] J.M. Kendra, T. Wachtendorf, Elements of resilience after the world trade center disaster: reconstituting New York City's emergency operations centre, *Disasters* 27 (1) (2003) 37–53.
- [160] L.A. Mallak, Measuring resilience in health care provider organizations, *Health Manpow. Manag.* 24 (4) (1998) 148–152.
- [161] R. Pal, H. Torstensson, H. Mattila, Antecedents of organizational resilience in economic crises—An empirical study of Swedish textile and clothing SMEs, *Int. J. Prod. Econ. Elsevier* 147 (PART B) (2014) 410–428.
- [162] B. Fahimnia, A. Jabbarzadeh, Marrying supply chain sustainability and resilience: a match made in heaven, *Transp. Res. E: Logist. Transp. Res. Rev.* 91 (2016) 306–324.
- [163] A. Gunasekaran, N. Subramanian, S. Rahman, Supply chain resilience: role of complexities and strategies, *Int. J. Prod. Res. Taylor Fr.* 53 (22) (2015) 6809–6819.
- [164] S.Y. Ponomarev, M.C. Holcomb, Understanding the concept of supply chain resilience, *Int. J. Logist. Manag.* 20 (1) (2009) 124–143.
- [165] J.-H. Thun, D. Hoenig, An empirical analysis of supply chain risk management in the German automotive industry, *Int. J. Prod. Econ.* 131 (1) (2011) 242–249.
- [166] S.A. Torabi, M. Baghersad, S.A. Mansouri, Resilient supplier selection and order allocation under operational and disruption risks, *Transp. Res. E: Logist. Transp. Res. Elsevier Ltd.* 79 (2015) 22–48.
- [167] D. Ivanov, Predicting the impacts of epidemic outbreaks on global supply chains: a simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case, *Transp. Res. E: Logist. Transp. Res. Elsevier* 136 (March) (2020) 101922.
- [168] A. Kumar, S. Luthra, S.K. Mangla, Y. Kazançoğlu, COVID-19 impact on sustainable production and operations management, *Sustain. Oper. Comput.* 1 (June) (2020) 1–7.
- [169] A. Rose, S.-Y. Liao, Modeling regional economic resilience to disasters: a computable general equilibrium analysis of water service disruptions, *J. Reg. Sci.* 45 (1) (2005) 75–112.

- [170] McKinney, W. (2010). "Data structures for statistical computing in Python." *Proceedings of the 9th Python in Science Conference*, S. van der Walt and J. Millman, eds., 56–61.
- [171] N. Reimers, I. Gurevych, Sentence-BERT: sentence embeddings using siamese BERT-networks. *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing*, Association for Computational Linguistics, 2019.
- [172] MacQueen, J. (1967). "Some methods for classification and analysis of multivariate observations."
- [173] P. Virtanen, R. Gommers, T.E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, S.J. van der Walt, M. Brett, J. Wilson, K.J. Millman, N. Mayorov, A.R.J. Nelson, E. Jones, R. Kern, E. Larson, C.J. Carey, Í. Polat, Y. Feng, E.W. Moore, J. VanderPlas, D. Laxalde, J. Perktold, R. Cimman, I. Henriksen, E.A. Quintero, C.R. Harris, A.M. Archibald, A. H. Ribeiro, F. Pedregosa, P. van Mulbregt, A. Vijaykumar, A. Pietro Bardelli, A. Rothberg, A. Hilboll, A. Kloeckner, A. Scopatz, A. Lee, A. Rokem, C.N. Woods, C. Fulton, C. Masson, C. Häggström, C. Fitzgerald, D.A. Nicholson, D.R. Hagen, D. V. Pasechnik, E. Olivetti, E. Martin, E. Wieser, F. Silva, F. Lenders, F. Wilhelm, G. Young, G.A. Price, G.-L. Ingold, G.E. Allen, G.R. Lee, H. Audren, I. Probst, J. P. Dietrich, J. Silterra, J.T. Webber, J. Slavič, J. Nothman, J. Buchner, J. Kulick, J. L. Schönberger, J.V. de Miranda Cardoso, J. Reimer, J. Harrington, J.L. C. Rodríguez, J. Nunez-Iglesias, J. Kuczynski, K. Tritz, M. Thoma, M. Newville, M. Kümmer, M. Bolingbroke, M. Tarte, M. Pak, N.J. Smith, N. Nowaczyk, N. Shebanov, O. Pavlyk, P.A. Brodtkorb, P. Lee, R.T. McGibbon, R. Feldbauer, S. Lewis, S. Tygier, S. Sievert, S. Vigna, S. Peterson, S. More, T. Pudlik, T. Oshima, T.J. Pingel, T.P. Robitaille, T. Spura, T.R. Jones, T. Cera, T. Leslie, T. Zito, T. Krauss, U. Upadhyay, Y.O. Halchenko, Y. Vázquez-Baeza, SciPy 1.0: fundamental algorithms for scientific computing in Python, *Nat. Methods* 17 (3) (2020) 261–272.
- [174] J.K. Pritchard, M. Stephens, P. Donnelly, Inference of population structure using multilocus genotype data, *Genetics* 155 (2) (2000) 945–959.
- [175] R. Rehürek, P. Sojka, Software framework for topic modelling with large Corpora, in: *Proceedings of the LREC 2010 Workshop on New Challenges for NLP Frameworks*, ELRA, Valletta, Malta, 2010, pp. 45–50.
- [176] L. van der Maaten, G.E. Hinton, Visualizing data using t-SNE, *J. Mach. Learn. Res.* 9 (2008) 2579–2605.
- [177] A.V. Aho, M.J. Corasick, Efficient string matching, *Commun. ACM* 18 (6) (1975) 333–340.
- [178] A.A. Hagberg, D.A. Schult, P.J. Swart, Exploring network structure, dynamics, and function using NetworkX, in: *7th Python in Science Conference (SciPy 2008)*, (SciPy), 2008, pp. 11–15.
- [179] B.W. Smith, J. Dalen, K. Wiggins, E. Tooley, P. Christopher, J. Bernard, The brief resilience scale: assessing the ability to bounce back, *Int. J. Behav. Med.* 15 (3) (2008) 194–200.
- [180] M. Scheffer, S. Carpenter, J.A. Foley, C. Folke, B. Walker, Catastrophic shifts in ecosystems, *Nature* 413 (6856) (2001) 591–596.
- [181] G. Windle, K.M. Bennett, J. Noyes, A methodological review of resilience measurement scales, *Health Qual. Life Outcomes* 9 (1) (2011) 8.
- [182] W.N. Adger, Social and ecological resilience: are they related? *Prog. Hum. Geogr.* 24 (3) (2000) 347–364.
- [183] S. Hosseini, K. Barker, J.E. Ramirez-Marquez, A review of definitions and measures of system resilience, *Reliab. Eng. Syst. Saf.* 145 (2016) 47–61.
- [184] G.E. Richardson, The metatheory of resilience and resiliency, *J. Clin. Psychol.* 58 (3) (2002) 307–321.
- [185] G.P. Cimellaro, A.M. Reinhorn, M. Bruneau, Framework for analytical quantification of disaster resilience, *Eng. Struct.* 32 (11) (2010) 3639–3649.
- [186] C. Folke, S.R. Carpenter, B. Walker, M. Scheffer, T. Chapin, J. Rockström, Resilience thinking: integrating resilience, adaptability and transformability, *Ecol. Soc.* 15 (4) (2010).
- [187] C. Folke, T. Hahn, P. Olsson, J. Norberg, Adaptive governance of social-ecological systems, *Annu. Rev. Environ. Resour.* 30 (1) (2005) 441–473.
- [188] G.C. Gallopín, Linkages between vulnerability, resilience, and adaptive capacity, *Glob. Environ. Change* 16 (3) (2006) 293–303.
- [189] S.B. Manyena, The concept of resilience revisited, *Disasters* 30 (4) (2006) 434–450.
- [190] C.S. Holling, Understanding the complexity of economic, ecological, and social systems, *Ecosystems* 4 (5) (2001) 390–405.
- [191] G. Windle, What is resilience? A review and concept analysis, *Rev. Clin. Gerontol. Camb. Univ. Press* 21 (2) (2011) 152–169.
- [192] R. Martin, Regional economic resilience, hysteresis and recessionary shocks, *J. Econ. Geogr.* 12 (1) (2012) 1–32.
- [193] M. Ungar, Resilience across cultures, *Br. J. Soc. Work* 38 (2) (2006) 218–235.
- [194] B.L. Turner, R.E. Kasperon, P.A. Matson, J.J. McCarthy, R.W. Corell, L. Christensen, N. Eckley, J.X. Kasperon, A. Luers, M.L. Martello, C. Polsky, A. Pulsipher, A. Schiller, A framework for vulnerability analysis in sustainability science, *Proc. Natl. Acad. Sci.* 100 (14) (2003) 8074–8079.
- [195] C.A. Lengnick-Hall, T.E. Beck, M.L. Lengnick-Hall, Developing a capacity for organizational resilience through strategic human resource management, *Hum. Resour. Manag. Rev.* 21 (3) (2011) 243–255.
- [196] S. Fergus, M.A. Zimmerman, Adolescent resilience: a framework for understanding healthy development in the face of risk, *Annu. Rev. Public Health* 26 (1) (2005) 399–419.
- [197] S.S. Luthar, D. Cicchetti, The construct of resilience: implications for interventions and social policies, *Dev. Psychopathol.* 12 (4) (2000) 857–885.
- [198] M. Rutter, Resilience as a dynamic concept, *Dev Psychopathol.* 24 (2) (2012 May) 335–344, <https://doi.org/10.1017/S0954579412000028>. PMID: 22559117.
- [199] S.M. Southwick, G.A. Bonanno, A.S. Masten, C. Panter-Brick, R. Yehuda, Resilience definitions, theory, and challenges: interdisciplinary perspectives, *Eur J Psychotraumatol* 5 (2014 Oct 1), <https://doi.org/10.3402/ejpt.v5.25338>. PMID: 25317257; PMCID: PMC4185134.
- [200] Y. Sheffi, J.J.B. Rice, A supply chain view of the resilient enterprise, *MIT Sloan Manag. Rev.* 47 (1) (2005).
- [201] M. Rutter, Implications of resilience concepts for scientific understanding, *Ann. N. Y. Acad. Sci.* 1094 (1) (2006) 1–12.
- [202] D. Henry, J. Emmanuel Ramirez-Marquez, Generic metrics and quantitative approaches for system resilience as a function of time, *Reliab. Eng. Syst. Saf.* 99 (2012) 114–122.
- [203] L. Campbell-Sills, S.L. Cohan, M.B. Stein, Relationship of resilience to personality, coping, and psychiatric symptoms in young adults, *Behav. Res. Ther.* 44 (4) (2006) 585–599.
- [204] M. Ungar, The social ecology of resilience: addressing contextual and cultural ambiguity of a nascent construct, *Am. J. Orthopsychiatry* 81 (1) (2011) 1–17.
- [205] T. Hu, D. Zhang, J. Wang, A meta-analysis of the trait resilience and mental health, *Personal. Individ. Differ.* 76 (2015) 18–27.
- [206] T. Elmqvist, C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, J. Norberg, Response diversity, ecosystem change, and resilience, *Front. Ecol. Environ. John Wiley Sons Ltd* 1 (9) (2003) 488–494.
- [207] D.L. Coutt, How resilience works, *Harv. bus. rev. U. S.* 80 (5) (2002) 46–50, 52, 55 passim.
- [208] A.D. Ong, C.S. Bergeman, T.L. Bisconti, K.A. Wallace, Psychological resilience, positive emotions, and successful adaptation to stress in later life, *J. Personal. Soc. Psychol.* 91 (4) (2006) 730–749.
- [209] D. Fletcher, M. Sarkar, Psychological resilience, *Eur. Psychol.* 18 (1) (2013) 12–23.
- [210] M. Ouyang, L. Dueñas-Orsorio, Time-dependent resilience assessment and improvement of urban infrastructure systems, *Chaos* 22 (3) (2012).
- [211] D.R. Bellwood, T.P. Hughes, C. Folke, M. Nyström, Confronting the coral reef crisis, *Nature* 429 (6994) (2004) 827–833.
- [212] C. Folke, S. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, B. Walker, Resilience and sustainable development: building adaptive capacity in a world of transformations, *AMBIO: J. Hum. Environ.* 31 (5) (2002) 437–440.
- [213] A. Feder, E.J. Nestler, D.S. Charney, Psychology and molecular genetics of resilience, *Nat. Rev. Neurosci.* 10 (6) (2009) 446–457.
- [214] E. Ostrom, A general framework for analyzing sustainability of social-ecological systems, *Science* 325 (5939) (2009) 419–422.
- [215] B. Walker, D. Salt, Resilience thinking: Sustaining ecosystems and People in a Changing World, Island Press, Washington, DC, 2006.
- [216] G. Peterson, C.R. Allen, C.S. Holling, Original Articles: Ecological Resilience, Biodiversity, and Scale, *Ecosystems* 1 (1) (Jan. 1998) 6–18, <https://doi.org/10.1007/s100219900002>.
- [217] K. Scholten, S. Schilder, The role of collaboration in supply chain resilience, *Supply Chain Manag.: Int. J.* 20 (4) (2015) 471–484.
- [218] G.P. Cimellaro, A.M. Reinhorn, M. Bruneau, Seismic resilience of a hospital system, *Struct. Infrastruct. Eng.* 6 (1–2) (2010) 127–144.
- [219] J. Simmie, R. Martin, The economic resilience of regions: towards an evolutionary approach, *Camb. J. Reg. Econ. Soc.* 3 (1) (2010) 27–43.
- [220] S.E. Chang, M. Shinozuka, Measuring improvements in the disaster resilience of communities, *Earthq. Spectra* 20 (3) (2004) 739–755.
- [221] M. Bruneau, A. Reinhorn, Exploring the concept of seismic resilience for acute care facilities, *Earthq. Spectra* 23 (1) (2007) 41–62.
- [222] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg, J. Vanderplas, A. Passos, D. Cournapeau, M. Brucher, M. Perrot, E. Duchesnay, Scikit-learn: machine learning in Python, *J. Mach. Learn. Res.* 12 (2011) 2825–2830.
- [223] M. Ouyang, Review on modeling and simulation of interdependent critical infrastructure systems, *Reliab. Eng. Syst. Saf.* Elsevier 121 (2014) 43–60.
- [224] H. Fawzi, P. Tabuada, S. Diggavi, Secure estimation and control for cyber-physical systems under adversarial attacks, *IEEE Trans. Autom. Control* 59 (6) (2014) 1454–1467.
- [225] I. Linkov, D.A. Eisenberg, K. Plourde, T.P. Seager, J. Allen, A. Kott, Resilience metrics for cyber systems, *Environ. Syst. Decis.* 33 (4) (2013) 471–476.
- [226] I. Zografopoulos, J. Ospina, X. Liu, C. Konstantinou, Cyber-physical energy Systems security: threat modeling, risk assessment, resources, metrics, and case studies, *IEEE Access* 9 (2021) 29775–29818.
- [227] S.A. Markolf, C. Hoehne, A. Fraser, M.V. Chester, B.S. Underwood, Transportation resilience to climate change and extreme weather events – Beyond risk and robustness, *Transp. Policy* 74 (2019) 174–186.
- [228] L. Galbusera, M. Cardarilli, G. Giannopoulos, The ERNCIP survey on COVID-19: emergency & Business continuity for fostering resilience in critical infrastructures, *Saf. Sci.* 139 (2021) 105161.
- [229] R. Biggs, M. Schlüter, D. Biggs, E.L. Bohensky, S. BurnSilver, G. Cundill, V. Dakos, T.M. Daw, L.S. Evans, K. Kotschy, A.M. Leitch, C. Meek, A. Quinlan, C. Raudsepp-Hearne, M.D. Robards, M.L. Schoon, L. Schultz, P.C. West, Toward principles for enhancing the resilience of ecosystem services, *Annu. Rev. Environ. Resour.* 37 (1) (2012) 421–448.
- [230] UNISDR. (2013). *Hyogo Framework for Action 2005–2015. United Nations*.
- [231] B. Kang, S.-J. Lee, D.-H. Kang, Y.-O. Kim, A flood risk projection for Yongdam dam against future climate change, *J. Hydro-environ. Res.* 1 (2) (2007) 118–125.
- [232] D. Butler, R. Farmani, G. Fu, S. Ward, K. Diao, M. Astaraie-Imani, A new approach to urban water management: safe and sure, *Procedia Eng.* 89 (2014) 347–354.
- [233] B. Allenby, J. Fink, Toward inherently secure and resilient societies, *Science* 309 (5737) (2005) 1034–1036.

- [234] C.A. Scott, C.J. Bailey, R.P. Marra, G.J. Woods, K.J. Ormerod, K. Lansey, Scenario planning to address critical uncertainties for robust and resilient water-wastewater infrastructures under conditions of water scarcity and rapid development, *Water (Switzerland)* 4 (4) (2012) 848–868.
- [235] Y.Y. Haimes, On the definition of resilience in systems, *Risk Anal.* 29 (4) (2009) 498–501.
- [236] M. Bruckler, L. Wietschel, L. Messmann, A. Thorenz, A. Tuma, Review of metrics to assess resilience capacities and actions for supply chain resilience, *Comput. Ind. Eng.* 192 (2024) 110176.
- [237] C. Nan, G. Sansavini, A quantitative method for assessing resilience of interdependent infrastructures, *Reliab. Eng. Syst. Saf.* Elsevier 157 (2017) 35–53.
- [238] E.D. Vugrin, D.E. Warren, M.A. Ehlen, A resilience assessment framework for infrastructure and economic systems: quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane, *Process Saf. Prog.* 30 (3) (2011) 280–290.
- [239] S. Shin, S. Lee, D. Judi, M. Parvania, E. Goharian, T. McPherson, S. Burian, A systematic review of quantitative resilience measures for water infrastructure systems, *Water* 10 (2) (2018) 164.
- [240] P. Amarasinghe, A. Liu, P. Egodawatta, P. Barnes, J. McGree, A. Goonetilleke, Quantitative assessment of resilience of a water supply system under rainfall reduction due to climate change, *J. Hydrol. Elsevier B.V* 540 (2016) 1043–1052.
- [241] T.R. Kjeldsen, D. Rosbjerg, Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems /Choix d'estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau, *Hydrol. Sci. J.* 49 (5) (2004).
- [242] M. Panteli, P. Mancarella, D.N. Trakas, E. Kyriakides, N.D. Hatzigiorgiou, Metrics and quantification of operational and infrastructure resilience in power systems, *IEEE Trans. Power Syst.* 32 (6) (2017) 4732–4742.
- [243] Y. Gu, X. Fu, Z. Liu, X. Xu, A. Chen, Performance of transportation network under perturbations: reliability, vulnerability, and resilience, *Transp. Res. E: Logist. Transp. Rev.* 133 (October 2019) (2020) 1–16.
- [244] R. Wright, M. Herrera, P. Pappas, I. Stoianov, Hydraulic resilience index for the critical link analysis of multi-feed water distribution networks, *Procedia Eng.* Elsevier B.V 119 (1) (2015) 1249–1258.
- [245] E. Miller-Hooks, X. Zhang, R. Faturechi, Measuring and maximizing resilience of freight transportation networks, *Comput. Oper. Res.* 39 (7) (2012) 1633–1643.
- [246] M. Herrera, E. Abraham, I. Stoianov, A graph-theoretic framework for assessing the resilience of sectorised water distribution networks, *Water Resour. Manag.* 30 (5) (2016) 1685–1699.
- [247] A. Wildavsky, *Searching For Safety*, Transaction Publishers, New Brunswick, NJ, 1988.
- [248] A. Sharifi, Y. Yamagata, Principles and criteria for assessing urban energy resilience: a literature review, *Renew. Sustain. Energy Rev.* 60 (2016) 1654–1677.
- [249] R.G. Little, Controlling cascading failure: understanding the vulnerabilities of interconnected infrastructures, *J. Urban Technol.* 9 (1) (2002) 109–123.
- [250] J.R. Harrold, Agility and discipline: critical success factors for disaster response, *ANN. Am. Acad. Polit. Soc. Sci.* 604 (1) (2006) 256–272.
- [251] S.E. Chang, T.L. McDaniels, J. Mikawoz, K. Peterson, Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice storm, *Nat. Hazards* 41 (2) (2007) 337–358.
- [252] T. McDaniels, S. Chang, K. Peterson, J. Mikawoz, D. Reed, Empirical Framework for characterizing infrastructure failure interdependencies, *J. Infrastruct. Syst.* 13 (3) (2007) 175–184.
- [253] V.R. Palleti, S. Adepu, V.K. Mishra, A. Mathur, Cascading effects of cyber-attacks on interconnected critical infrastructure, *Cybersecurity* 4 (1) (2021) 8.
- [254] C. Perrow, *Normal Accidents: Living With High-Risk Technologies*, Princeton University Press, Princeton, NJ, 1999.
- [255] E.M. Wells, M. Boden, I. Tseytlin, I. Linkov, Modeling critical infrastructure resilience under compounding threats: a systematic literature review, *Prog. Disaster Sci. Elsevier Ltd* 15 (May) (2022) 100244.
- [256] A. Brezar, C. Skopeliti, Spain, Portugal and parts of France hit by massive power outage, *Euronews* (2025).
- [257] J. Fiksel, Designing resilient, sustainable systems, *Environ. Sci. Technol.* 37 (23) (2003) 5330–5339.
- [258] M.E. Krasny, K.G. Tidball, Applying a resilience systems framework to urban environmental education, *Environ. Educ. Res.* 15 (4) (2009) 465–482.
- [259] W.N. Adger, T.P. Hughes, C. Folke, S.R. Carpenter, J. Rockström, Social-ecological resilience to coastal disasters, *Science* 309 (5737) (2005) 1036–1039.
- [260] E.L. Tompkins, W.N. Adger, Does adaptive management of natural resources enhance resilience to climate change? *Ecol. Soc.* 9 (2) (2004) art10.
- [261] F. Heylighen, The science of self-organization and adaptivity, in: L.D. Kiel (Ed.), *Knowledge Management, Organizational Intelligence and Learning, and Complexity. The Encyclopedia of Life Support Systems, Knowledge Management, Organizational Intelligence and Learning, and Complexity. The Encyclopedia of Life Support Systems*, 5, Eolss Publishers, Oxford, UK, 2001, pp. 1–26.
- [262] F. Berkes, Understanding uncertainty and reducing vulnerability: lessons from resilience thinking, *Nat. Hazards* 41 (2) (2007) 283–295.
- [263] D. Bouziotas, D. van Duuren, H.-J. van Alphen, J. Frijns, D. Nikolopoulos, C. Makropoulos, Towards circular water neighborhoods: simulation-based decision support for integrated decentralized urban water systems, *Water* 11 (6) (2019) 1227.
- [264] D. Bouziotas, S. Stofberg, J. Frijns, D. Nikolopoulos, C. Makropoulos, Assessing the resilience of circularity in water management: a modeling framework to redesign and stress-test regional systems under uncertainty, *Urban Water J.* 20 (5) (2023) 532–549.
- [265] D. Nikolopoulos, H.-J. van Alphen, D. Vries, L. Palmen, S. Koop, P. van Thienen, G. Medema, C. Makropoulos, Tackling the ‘new normal’: a resilience assessment method applied to real-world urban water systems, *Water* 11 (2) (2019) 330.
- [266] A. Zahediasl, A.E. Bakhshpour, U. Dittmer, A. Haghighi, Toward decentralised sanitary sewage collection systems: a multiobjective approach for cost-effective and resilient designs, *Water (Switzerland)* 13 (14) (2021).
- [267] A. Munoz, J. Billsberry, V. Ambrosini, Resilience, robustness, and antifragility: towards an appreciation of distinct organizational responses to adversity, *Int. J. Manag. Res. Rev.* 24 (2) (2022) 181–187.
- [268] N.N. Taleb, *Antifragile: Things That Gain from Disorder*, Random House, New York, 2012.
- [269] S. Mafabi, J. Munene, J. Ntayi, Knowledge management and organisational resilience, *J. Strategy Manag.* 5 (1) (2012) 57–80.
- [270] A. Rose, Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions, *Environ. Hazards* 7 (4) (2007) 383–398.
- [271] C.L. Redman, Should sustainability and resilience Be combined or remain distinct pursuits? *Ecol. Soc.* 19 (2) (2014) art37.
- [272] M. Cote, A.J. Nightingale, Resilience thinking meets social theory, *Prog. Hum. Geogr.* 36 (4) (2012) 475–489.
- [273] D. Marchese, E. Reynolds, M.E. Bates, H. Morgan, S.S. Clark, I. Linkov, Resilience and sustainability: similarities and differences in environmental management applications, *Sci. Total Environ. Elsevier B.V* 613–614 (2018) 1275–1283.
- [274] J. Rockström, W. Steffen, K. Noone, Å. Persson, F.S. Chapin, E.F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, J.A. Foley, A safe operating space for humanity, *Nature* 461 (7263) (2009) 472–475.
- [275] W. Steffen, Å. Persson, L. Deutsch, J. Zalasiewicz, M. Williams, K. Richardson, C. Crumley, P. Crutzen, C. Folke, L. Gordon, M. Molina, V. Ramanathan, J. Rockström, M. Scheffer, H.J. Schellnhuber, U. Svedin, The anthropocene: from global change to planetary stewardship, *Ambio* 40 (7) (2011) 739–761.
- [276] W.C. on E. and D. WCED, *Our Common Future*, Oxford University Press, Oxford, UK, 1987.
- [277] J.M. Anderies, C. Folke, B. Walker, E. Ostrom, Aligning key concepts for global change policy: robustness, resilience, and sustainability, *Ecol. Soc.* 18 (2) (2013).
- [278] H. Hiessl, R. Walz, D. Toussaint, Design and sustainability assessment of scenarios of urban water infrastructure systems, in: *5th International Conference on Technology Policy and Innovation*, the Netherlands, 2001, p. 11.
- [279] W.E. Rees, Achieving sustainability: reform or transformation? *J. Plan. Lit.* 9 (4) (1995) 343–361.
- [280] S. Meerow, J.P. Newell, Urban resilience for whom, what, when, where, and why? *Urban Geogr. Routledge* 40 (3) (2019) 309–329.
- [281] D. McEvoy, H. Fünfgeld, K. Bosomworth, Resilience and climate change adaptation: the importance of framing, *Plan. Pract. Res.* 28 (3) (2013) 280–293.
- [282] B. Hopwood, M. Mellor, G. O'Brien, Sustainable development: mapping different approaches, *Sustain. Dev.* 13 (1) (2005) 38–52.
- [283] R. Friend, M. Moench, What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability, *Urban Clim. Elsevier Ltd* 6 (2013) 98–113.
- [284] D. MacKinnon, K.D. Derickson, From resilience to resourcefulness, *Prog. Hum. Geogr.* 37 (2) (2013) 253–270.
- [285] D. Matyas, M. Pelling, Positioning resilience for 2015: the role of resistance, incremental adjustment and transformation in disaster risk management policy, *Disasters* 39 (s1) (2015) s1–s18.
- [286] R. Cretney, Resilience for whom? Emerging critical geographies of socio-ecological resilience, *Geogr. Compass* 8 (9) (2014) 627–640.
- [287] J. Joseph, Resilience as embedded neoliberalism: a governmentality approach, *Resilience* 1 (1) (2013) 38–52.
- [288] J.P. Evans, Resilience, ecology and adaptation in the experimental city, *Trans. Inst. Br. Geogr.* 36 (2) (2011) 223–237.
- [289] C. Wamsler, *Cities, Disaster Risk and Adaptation*, Routledge, 2014.
- [290] T. Aven, Risk assessment and risk management: review of recent advances on their foundation, *Eur. J. Oper. Res. Elsevier B.V* 253 (1) (2016) 1–13.
- [291] Y.Y. Haimes, On the complex definition of risk: a systems-based approach, *Risk Anal.* 29 (12) (2009) 1647–1654.
- [292] D. Garrick, J.W. Hall, Water security and society: risks, metrics, and pathways, *Annu. Rev. Environ. Resour.* 39 (1) (2014) 611–639.
- [293] W.W. Lowrance, *Of Acceptable Risk*, William Kaufmann, Los Altos, CA, 1976.
- [294] S. Kaplan, B.J. Garrick, On the quantitative definition of risk, *Risk Anal.* 1 (1) (1981) 11–27.
- [295] Y.Y. Haimes, W.A. Hall, Sensitivity, responsivity, stability and irreversibility as multiple objectives in civil systems, *Adv. Water Resour.* 1 (2) (1977) 71–81.
- [296] F. Knight, *Risk, Uncertainty and Profit*, Houghton Mifflin Company, Boston, New York, 1921.
- [297] R. Pawson, G. Wong, L. Owen, Known knowns, Known unknowns, unknown unknowns, *Am. J. Eval.* 32 (4) (2011) 518–546.
- [298] N.N. Taleb, *The Black Swan: The Impact of the Highly Improbable*, Random House, New York, 2007.
- [299] W.E. Walker, M. Haasnoot, J.H. Kwakkel, Adapt or perish: a review of planning approaches for adaptation under deep uncertainty, *Sustain. (Switz.)* 5 (3) (2013) 955–979.
- [300] W.E. Walker, R.J. Lempert, J.H. Kwakkel, *Deep Uncertainty. Encyclopedia of Operations Research and Management Science*, Springer US, Boston, MA, 2013, pp. 395–402.

- [301] R.J. Lempert, S.W. Popper, S.C. Bankes, Shaping the next one hundred years: new methods for quantitative, long-term policy analysis, *Technol. Forecast. Soc. Change* 71 (3) (2004) 305–307.
- [302] S.L. Cutter, Vulnerability to environmental hazards, *Prog. Hum. Geogr.* 20 (4) (1996) 529–539.
- [303] P. O'Hare, I. White, Deconstructing resilience: lessons from planning practice, *Plan. Pract. Res.* 28 (3) (2013) 275–279.
- [304] B. Smit, J. Wandel, Adaptation, adaptive capacity and vulnerability, *Glob. Environ. Change* 16 (3) (2006) 282–292.
- [305] J.X. Kasperson, R.E. Kasperson, *Global Environmental Risk*, United Nations University Press/Earthscan, London, UK, 2001.
- [306] G.A. Wilson, Community resilience, globalization, and transitional pathways of decision-making, *Geoforum Elsevier Ltd* 43 (6) (2012) 1218–1231.
- [307] M. Pelling, *The Vulnerability of Cities: Natural Disasters and Social Resilience*, Earthscan, London, UK, 2003.
- [308] K. Sherrieb, F.H. Norris, S. Galea, Measuring capacities for community resilience, *Soc. Indic. Res.* 99 (2) (2010) 227–247.
- [309] O.R. Young, Institutional dynamics: resilience, vulnerability and adaptation in environmental and resource regimes, *Glob. Environ. Change Elsevier Ltd* 20 (3) (2010) 378–385.
- [310] Gallopín, G.C. (2003). *A Systems Approach to Sustainability and Sustainable development. Buletinul Institutului De Studii si Proiectari Energetice English ed.*, Santiago, Chile.
- [311] S.A. Argyroudis, S.A. Mitoulis, L. Hofer, M.A. Zanini, E. Tubaldi, D.M. Frangopol, Resilience assessment framework for critical infrastructure in a multi-hazard environment: case study on transport assets, *Sci. Total Environ. Elsevier B.V* 714 (2020) 136854.
- [312] M. Theodoridou, G. Giannopoulos, Risk assessment methodologies for critical infrastructure protection. Part II: a new approach, in: *European Commission JRC (Joint Research Center) Technical Notes*, 2015, Publications Office of the European Union, Luxembourg, 2015.
- [313] J.D. Herman, P.M. Reed, H.B. Zeff, G.W. Characklis, How should robustness be defined for water systems planning under change? *J. Water Resour. Plan. Manag.* 141 (10) (2015) 04015012.
- [314] N. Matalas, M.B. Fiering, *Water-resource systems planning. Climate, Climatic Change, and Water Supply*, The National Academies Press, Washington, D.C., 1977, pp. 99–110.
- [315] J.M. Carlson, J. Doyle, Complexity and robustness, *Proc. Natl. Acad. Sci.* 99 (suppl_1) (2002) 2538–2545.
- [316] M. Homayounfar, R. Muneeppeerakul, J.M. Anderies, C.P. Muneeppeerakul, Linking resilience and robustness and uncovering their trade-offs in coupled infrastructure systems, *Earth Syst. Dyn.* 9 (4) (2018) 1159–1168.
- [317] E. Krueger, P.S.C. Rao, D. Borchardt, Quantifying urban water supply security under global change, *Glob. Environ. Change Elsevier Ltd* 56 (April 2018) (2019) 66–74.
- [318] D. Read, Some observations on resilience and robustness in human systems, *Cybern. Syst.* 36 (8) (2005) 773–802.
- [319] J. Jasiūnas, P.D. Lund, J. Mikkola, Energy system resilience – a review, *Renew. Sustain. Energy Rev.* 150 (2021) 111476.
- [320] D. Nikolopoulos, P. Kossieris, I. Tsoukalas, C. Makropoulos, Stress-testing framework for urban water systems: a source to tap approach for stochastic resilience assessment, *Water* 14 (2) (2022) 154.
- [321] A. Größler, A managerial operationalization of antifragility and its consequences in supply chains, *Syst. Res. Behav. Sci.* 37 (6) (2020) 896–905.
- [322] A. Boin, M.J.G. van Eeten, The resilient organization, *Public Manag. Rev.* 15 (3) (2013) 429–445.
- [323] J. Hillmann, E. Guenther, Organizational resilience: a valuable construct for management research? *Int. J. Manag. Rev.* 23 (1) (2021) 7–44.
- [324] D. Nikolopoulos, C. Makropoulos, A novel cyber-physical resilience-based strategy for water quality sensor placement in water distribution networks, *Urban Water J.* (2023).
- [325] European Union. (2022a). “Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union, amending Regulation (EU) No 910/2014 and Directive (EU) 2018/1972, and repealing Directive (EU) 2016/1148 (NIS2 Directive).”.
- [326] European Union. (2022b). “Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC (CER Directive).”.
- [327] PPD-21. (2013). *Presidential policy directive – critical infrastructure security and resilience*.
- [328] M.J. Alexopoulos, A. Niemi, B. Skobiej, F. Sill Torres, Examination of the Critical infrastructure resilience Directive from the maritime point of view, *JCMS: J. Common Mark. Stud.* 63 (2) (2025) 667–678.
- [329] International Organization for Standardization. (2018). “Risk management – guidelines.”.
- [330] International Organization for Standardization. (2019). “Security and resilience – business continuity management systems – requirements.”.
- [331] United Nations Office for Disaster Risk Reduction (UNDRR). (2022). *Principles for resilient infrastructure. Principles for resilient infrastructure*.
- [332] G. Moraitis, G.-K. Sakki, G. Karavokiros, D. Nikolopoulos, I. Tsoukalas, P. Kossieris, C. Makropoulos, Exploring the cyber-physical threat landscape of water systems: a socio-technical modelling approach, *Water* 15 (9) (2023) 1687.
- [333] M. Haggag, M. Ezzeldin, W. El-Dakhkhni, E. Hassini, Resilient cities critical infrastructure interdependence: a meta-research, *Sustain. Resilient Infrastruct. Taylor Fr.* 7 (4) (2022) 291–312.
- [334] W. Kröger, Critical infrastructures at risk: a need for a new conceptual approach and extended analytical tools, *Reliab. Eng. Syst. Saf.* 93 (12) (2008) 1781–1787.
- [335] S. Dunn, M. Holmes, Development of a hierarchical approach to analyse interdependent infrastructure system failures, *Reliab. Eng. Syst. Saf.* 191 (2019) 106530.
- [336] J.R. Thompson, D. Frezza, B. Necioglu, M.L. Cohen, K. Hoffman, K. Rosford, Interdependent Critical Infrastructure Model (ICIM): an agent-based model of power and water infrastructure, *Int. J. Crit. Infrastruct. Prot.* 24 (2019) 144–165.
- [337] S.V. Croom, S. McNeil, Improving resilience of critical infrastructure systems postdisaster, *Transp. Res. Rec.: J. Transp. Res. Board* 2234 (1) (2011) 3–13.
- [338] S.C. Muller, H. Georg, J.J. Nutaro, E. Widl, Y. Deng, P. Palensky, M.U. Awais, M. Chenine, M. Kuch, M. Stifter, H. Lin, S.K. Shukla, C. Wietfeld, C. Rehtanz, C. Dufour, X. Wang, V. Dinavahi, M.O. Faruque, W. Meng, S. Liu, A. Monti, M. Ni, A. Davoudi, A. Mehrizi-Sani, Interfacing Power system and ICT simulators: challenges, State-of-the-art, and case studies, *IEEE Trans. Smart Grid* 9 (1) (2018) 14–24.
- [339] J.J. Magoua, F. Wang, N. Li, High level architecture-based framework for modeling interdependent critical infrastructure systems, *Simul. Model. Pract. Theory Elsevier B.V* 118 (March) (2022) 102529.
- [340] F. Wang, J.J. Magoua, N. Li, Modeling cascading failure of interdependent critical infrastructure systems using HLA-based co-simulation, *Autom. Constr.* 133 (2022) 104008.
- [341] “IEEE standard for modeling and simulation (M&S) high level architecture (HLA) – framework and rules.” (2010). IEEE, Piscataway, NJ, USA.
- [342] I. Eusgeld, C. Nan, S. Dietz, System-of-systems’ approach for interdependent critical infrastructures, *Reliab. Eng. Syst. Saf.* 96 (6) (2011) 679–686.
- [343] G. Lampropoulos, X. Larrucea, R. Colomo-Palacios, Digital twins in critical infrastructure, *Information* 15 (8) (2024) 454.
- [344] R. Cantelmi, G. Di Gravio, R. Patriarca, Reviewing qualitative research approaches in the context of critical infrastructure resilience, *Environ. Syst. Decis. Springer US* 41 (3) (2021) 341–376.
- [345] B. Rathnayaka, C. Siriwardana, D. Robert, D. Amaratunga, S. Setunge, Improving the resilience of critical infrastructures: evidence-based insights from a systematic literature review, *Int. J. Disaster Risk Reduct. Elsevier Ltd* 78 (May) (2022) 103123.
- [346] C. Lomba-Fernández, J. Hernantes, L. Labaka, Guide for climate-resilient cities: an urban critical infrastructures approach, *Sustainability* 11 (17) (2019) 4727.
- [347] Bakalinskyi, O. and McDonough, M. (2025) *Ukraine’s wartime experience provides blueprint for infrastructure protection*, *Atlantic Council*. Available at: <https://www.atlanticcouncil.org/blogs/ukrainealert/ukraines-wartime-experience-provides-blueprint-for-infrastructure-protection/> (Accessed: 4 February 2026).
- [348] H. Horan, et al., *Assessing Europe’s Resilience and Preparedness in an Era of Strategic Risks*, The Hague, The Netherlands, 2025.
- [349] Humphreys, B.E. (2024) *Attacks On Ukraine’s Electric Grid: Insights for U.S. Infrastructure Security and Resilience*. Washington, D.C., USA.
- [350] F. Diaz-Maurin, Ukrainian dam is destroyed; nuclear plant lives in a ‘grace period’, *Bull. At. Sci.* (2023). Available at: <https://thebulletin.org/2023/06/ukrainian-dam-is-destroyed-nuclear-plant-lives-in-a-grace-period/> (Accessed: 4 February 2026).