PLOS CLIMATE

REVIEW

Quantifying climate risks to infrastructure systems: A comparative review of developments across infrastructure sectors

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Citation: Verschuur J, Fernández-Pérez A, Mühlhofer E, Nirandjan S, Borgomeo E, Becher O, et al. (2024) Quantifying climate risks to infrastructure systems: A comparative review of developments across infrastructure sectors. PLOS Clim 3(4): e0000331. https://doi.org/10.1371/journal.pclm.0000331

Editor: Thomas Thaler, University of Natural Resources and Life Sciences, AUSTRIA

Published: April 4, 2024

Funding: J.V. acknowledges funding from the Oxford Martin School Programme on Systemic Resilience and from the Engineering and Physical Sciences Research Council (EPSRC) under grant number EP/W524311/1. E.E.K. was supported by the Dutch Research Council (NWO) (Grant No. VI. Veni.194.033). E.E.K., J.W.H., S.N. and R.P. received funding from EU-H2020 MIRACA, grant no. 101004174. J.W.H and R.P. also received support from the Climate Compatible Growth Programme funded by the UK FCDO. A.FP. acknowledges funding from the Spanish Ministry of Science, Innovation and Universities under grant number FPU2019-00532. A.J. and S.F.G.

Abstract

Infrastructure systems are particularly vulnerable to climate hazards, such as flooding, wildfires, cyclones and temperature fluctuations. Responding to these threats in a proportionate and targeted way requires quantitative analysis of climate risks, which underpins infrastructure resilience and adaptation strategies. The aim of this paper is to review the recent developments in quantitative climate risk analysis for key infrastructure sectors, including water and wastewater, telecommunications, health and education, transport (seaports, airports, road, rail and inland waterways), and energy (generation, transmission and distribution). We identify several overarching research gaps, which include the (i) limited consideration of multi-hazard and multi-infrastructure interactions within a single modelling framework, (ii) scarcity of studies focusing on certain combinations of climate hazards and infrastructure types, (iii) difficulties in scaling-up climate risk analysis across geographies, (iv) increasing challenge of validating models, (v) untapped potential of further knowledge spillovers across sectors, (vi) need to embed equity considerations into modelling frameworks, and (vii) quantifying a wider set of impact metrics. We argue that a cross-sectoral systems approach enables knowledge sharing and a better integration of infrastructure interdependencies between multiple sectors.

Introduction

Infrastructure systems can be defined as “the coordinated operation and management of a group of physical assets to perform a range of processes and thereby providing infrastructure

acknowledge funding from the Swiss Federal Office of Energy (SFOE). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

services to users" [1]. These include systems of energy, water, telecommunications, transport, and waste infrastructure, along with social infrastructure (hospitals, schools etc.) in some definitions. The services that these infrastructures provide are fundamental to modern society and underpin the Sustainable Development Goals (SDGs) [2]. There are strong links between climate and infrastructure, amongst others; (i) infrastructure systems are vulnerable and exposed to climate hazards [3], (ii) decarbonising the economy requires substantial infrastructure investments [4], (iii) changes in climate influence the demand for infrastructure services (e.g., energy for cooling) [5, 6] and (iv) adapting infrastructures to climate change is critical to safeguard economic development [7, 8].

It has been estimated that by 2050 a total of USD 9.2 trillion of investments would be required to address infrastructure deficits (that is, to meet infrastructure demand for future societies), attain the SDGs, and achieve net zero [9]. Expanding the stock of infrastructure, in particular in low and middle income countries, will lead to an increasing amount of such infrastructure exposed to climate hazards. While at present the average annual damages to infrastructure and buildings equate to around USD 700 billion per year (from climatic and non-climatic hazards) [10], this number is expected to increase several fold over the 21st century because of climate change and the aforementioned expansion of infrastructure assets, especially in urban built-up areas in hazard-prone locations such as floodplains [11].

To identify climate risks, develop resilience strategies and prioritise adaptation investments, quantified climate risk analysis is key, both for existing and newly planned infrastructure [1]. Over the last years, major progress has taken place in the development of quantitative analytical frameworks to quantify present and future climate hazards to infrastructure systems. Yet, reviews and stocktakes of these developments have mainly been performed for infrastructure sectors separately [12–16]. This has prevented comparing and contrasting such developments across infrastructure types to foster cross-sectoral learning and collaboration.

In this article, we provide a review summarizing the recent research developments in quantifying climate risks to infrastructure systems across sectors, thereby providing a more holistic view on advances made in the field. We identify seven overarching research gaps in existing analytical approaches, allowing us to draw up a research agenda that is of wider interest to the research community working on infrastructure and climate risks.

We start by providing a brief overview of the climate risks faced by different infrastructure types, contextualised in recent events. This is followed by a description of main strands of analytical approaches to quantify the impacts of climate hazards per infrastructure sector. We then identify several limitations and gaps within the literature and discuss various ways to overcome them. In line with other review papers [17–19], we rely on expert judgment of the authors to characterize the vulnerability of infrastructure to various hazards, and synthesize the existing literature to derive various research strands per infrastructure sector considered.

The infrastructure sectors considered are water (water and wastewater collection and treatment), telecommunications, social infrastructure (health and education), transport (seaports, airports, road, rail and inland water transport), and energy (generation, transmission and distribution). In the following, we refer to all hazards considered simply as climate hazards, which capture hazards that are sometimes referred to as extreme weather events, climate extremes, or natural hazards.

Climate risks to infrastructure

Different infrastructure systems are often co-located (e.g., in densely populated areas) [20], and hence share similarities in terms of their exposure to climate hazards. However, how vulnerable the different infrastructures are to these risks (that is, how exposure to a climate hazard lead to damages and service disruptions) and the impacts of them (that is, the severity of the impacts if disrupted in terms of damages and service disruptions) differs across hazards and infrastructure sectors. The term climate risk in this study refers to the potential for adverse consequences to infrastructure systems, and to those that rely upon them (e.g., dependent infrastructure, livelihoods, economy, ecosystems), as a result of climate hazard impacts, which is shaped by the exposure of infrastructure assets to climate hazards, the vulnerability of those systems to withstand these hazards, and the ability of the infrastructure systems to recover after adverse impacts.

Similar as in previous studies [17, 18], we use expert judgement of the review authors and map these differences at the high-level global scale in the bivariate plot in Fig 1, with both vulnerability and impacts scaled from low vulnerability/impact to high vulnerability/impact. Most infrastructure sectors have one or multiple dominant climate hazards, such as flooding for road, rail and electricity generation, cyclone wind for seaports, airports, telecom and electricity transmission, droughts for water and inland water transport, sea-level rise for seaports and airports, and salinity intrusion for water. In other words, despite their co-location, different infrastructure systems require specific design considerations for the climate hazards they are exposed to, alongside considerations of multi-hazard interactions (i.e., the occurrence of cascading, consecutive or concurrent hazard impacts to infrastructure systems).

Recent disruptive events have confirmed those combinations of high vulnerability and impact for specific infrastructure sectors. Fig 2 shows the geolocation of major recent events

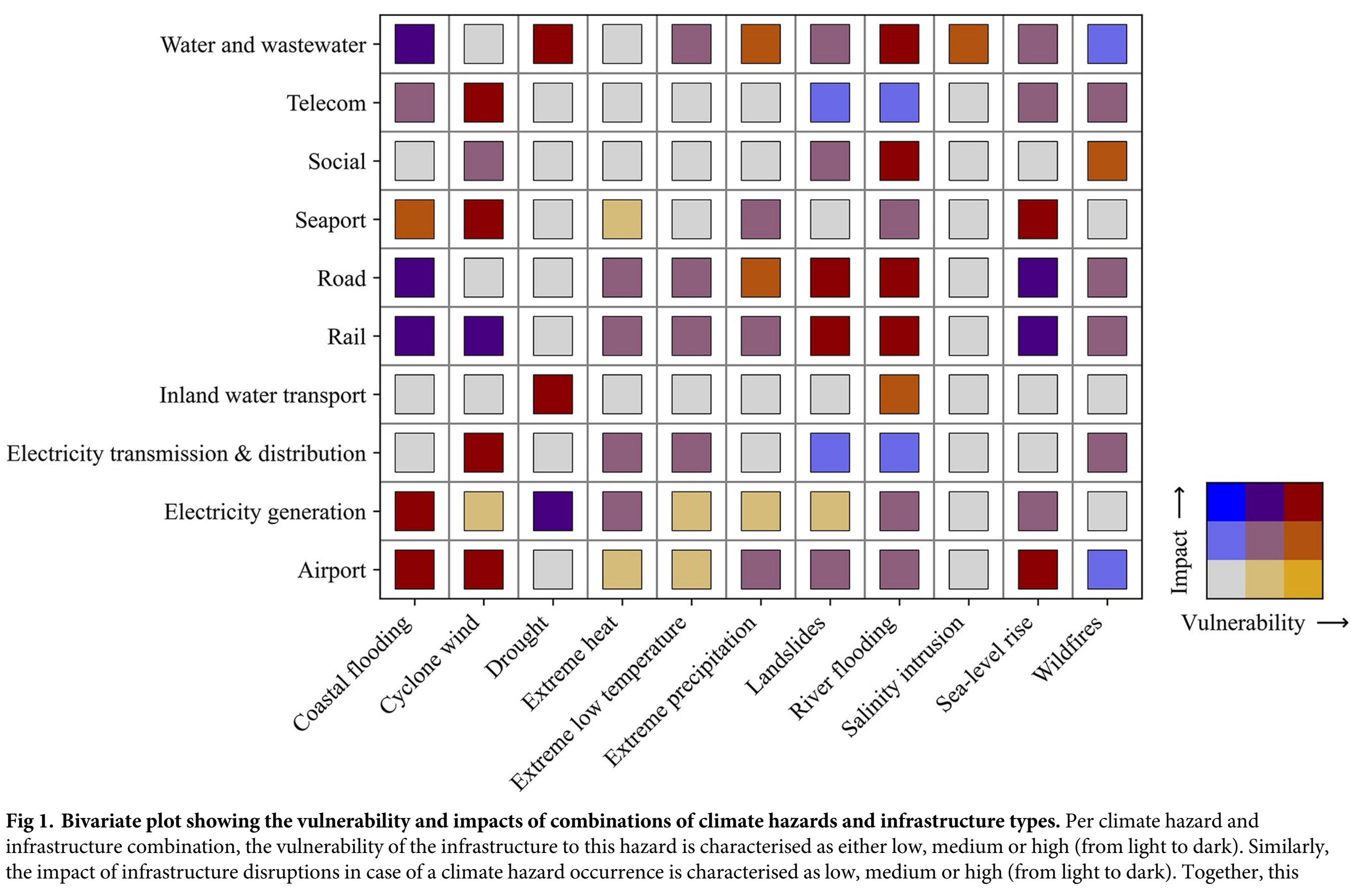

Fig 1. Bivariate plot showing the vulnerability and impacts of combinations of climate hazards and infrastructure types. Per climate hazard and infrastructure combination, the vulnerability of the infrastructure to this hazard is characterised as either low, medium or high (from light to dark). Similarly, the impact of infrastructure disruptions in case of a climate hazard occurrence is characterised as low, medium or high (from light to dark). Together, this creates a risk classification system of nine different types of combinations, as indicated by the colours. This characterisation is based on expert judgment of the review authors.

https://doi.org/10.1371/journal.pclm.0000331.g001

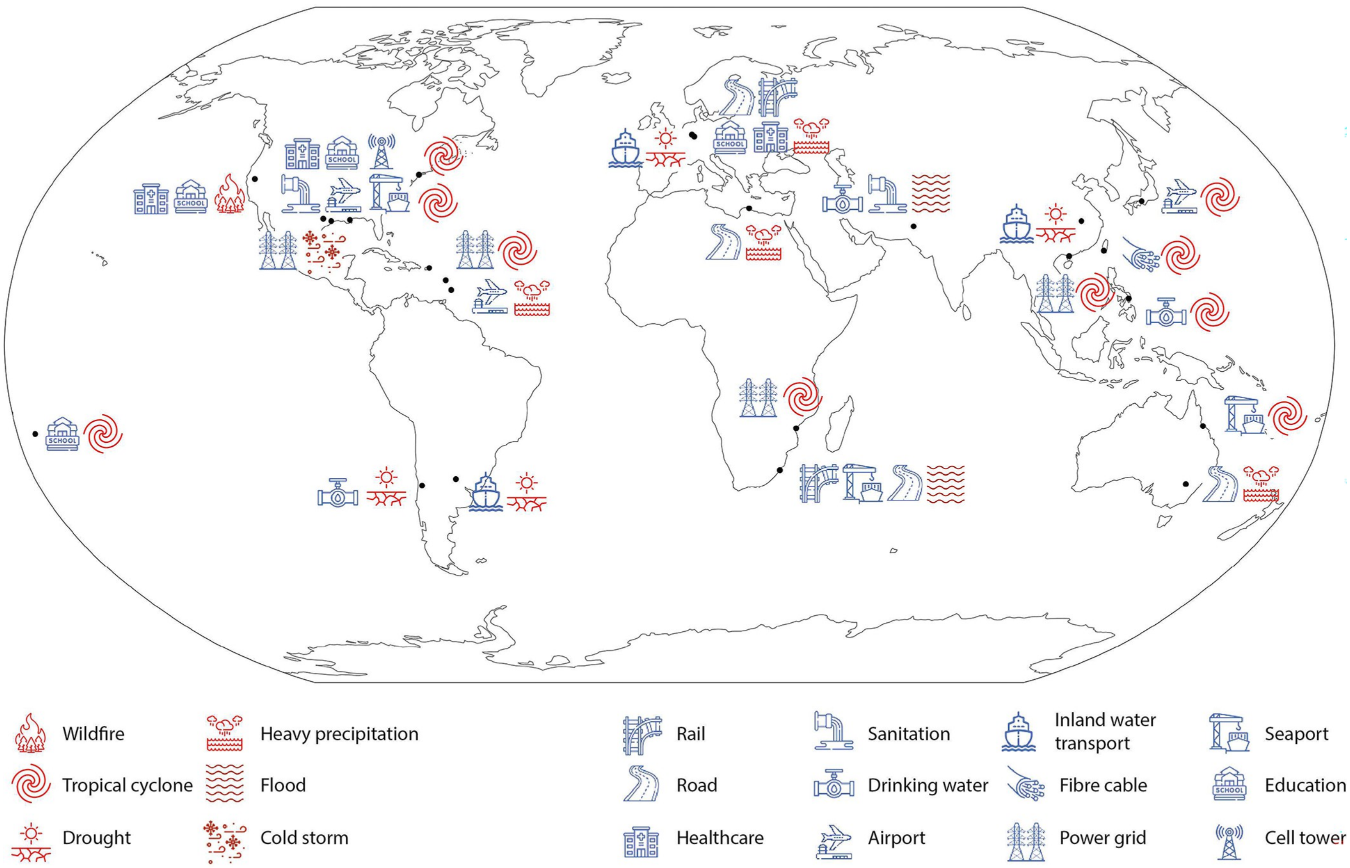

Fig 2. Map showing the location, climate hazards and affected infrastructure for a subset of recent high impact events. Further details are provided in S1 Table. The basemap used in this Fig is from the Global Administrative Areas (GADM) database (https://gadm.org/).

https://doi.org/10.1371/journal.pclm.0000331.g002

that have caused havoc to the different infrastructure sectors, with S1 Table describing the physical damages and service disruptions experienced during these events.

These events provided valuable lessons learned. First of all, while major catastrophic events can cause damages and disruptions across infrastructure sectors, the service disruption and speed of recovery can differ widely. After the European Floods in 2021, which disrupted transport, electricity, water, telecom and social infrastructure, the expected recovery duration across these infrastructure sectors ranged from weeks to multiple years, with water and electricity being prioritized for faster recovery times and transport infrastructure recovery taking the longest [21].

Second, several reported impacts are often caused by infrastructure interdependencies (i.e., cascading impacts), where disruptions to a specific infrastructure service was initiated by an initial disruption to another infrastructure sector. For instance, during the 2018 Camp Fire wildfires in California, damages to the electricity system hampered the provision of electricity to schools, leading to closures of schools and temporary relocation [22]. During the 2022 Kwa-Zulu-Natal Floods, the main access road to the port of Durban was damaged, which led to operational disruptions at South Africa's largest port [23].

Third, reconstruction efforts to rebuild infrastructure and restore services can itself be hampered by infrastructure disruptions. Storm Daniel (2023), for instance, caused major flood impacts to roads, bridges and the telecom infrastructure in the city of Derna (Libya), which trapped residents, prevented effective rescue operations, and made recovery efforts challenging [24].

Quantifying climate risks to infrastructure

The following sections briefly summarise some of the advances made in quantifying climate risks to infrastructure systems. These summaries are intended to capture the main research strands and recent innovations in terms of analytical modelling frameworks per sector.

Climate risks to infrastructure systems can broadly be categorised in four tiers, as proposed by Dawson et al. [17], and summarised in Fig 3. The first tier involves quantifying the risk to individual assets, such as the physical asset damages from flooding of road segments or from heat to energy transmission. Within the second tier, network-wide effects are evaluated, considering damages to multiple components of the transportation system and their implications, such as the disruption of train services due to floods destroying railway lines. The third tier focuses on analysing interactions and dependencies between infrastructure networks, such as the flooding of a nearby electricity substation that leads to the disruption of an airport or water treatment plant. Finally, the fourth tier entails assessing systemic risks associated with the indirect economic losses or other socio-economic impacts of infrastructure services. When going to higher tiers, the spatial scale often increases, resulting in an amplification of impacts. However, capturing these higher tiers effects also increases the complexity of quantitative modelling frameworks, and hence the ability to validate model results. We can refer to these three aspects as the key modelling trade-offs.

The monetary or non-monetary impacts associated with risk could refer to a wide range of metrics—including physical asset damages, operational disruptions, revenue losses, customers impacted, supply-chain losses, environmental impacts, fiscal impacts and welfare losses. We would like to redirect interested readers to other reviews for a more detailed discussion on the wide spectrum of impacts to infrastructure systems [3, 10].

Road and rail transport

Road and railway infrastructure are prone to a multitude of climate hazards (Fig 1), which are expected to increase rapidly due to climate change [25]. For each of the four-tiers (see Fig 3), several research advances have been made with the aim of producing monetary estimates, some of which within real data-based case studies. For road and rail assets, climate vulnerability thresholds have been produced [16, 26], which have formed the basis for physical asset damage estimates (tier one) from multiple hazards at the global scale under current climate [27] and at the European scale under future climate change driven scenarios [28]. These methods for physical asset damage estimations are quite well established and more scalable from asset scale to global scale because; (1) of the availability of increasingly good open-source harmonised road and rail asset location data [20]; (2) such impacts are also additive in nature, where damages of individual assets can be summed up together to estimate damages at aggregated scales [27].

Service disruptions (tier two) have been estimated for more regional case studies, such as the impacts of flood-induced failures to railway bridges in Great Britain [29] or the impact of hurricane Harvey on regional transport flows in Houston [30]. Systemic risk estimates (tier three and tier four) for individual network link failures of interdependent road and rail networks exposed to climate change driven hazards have been estimated at the national scales for Vietnam [31], Argentina [32] and at the regional scale for East Africa [33].

Estimating these higher-tier impacts in terms of service disruptions and indirect economic losses requires detailed information on passenger and freight traffic flows and economic sector

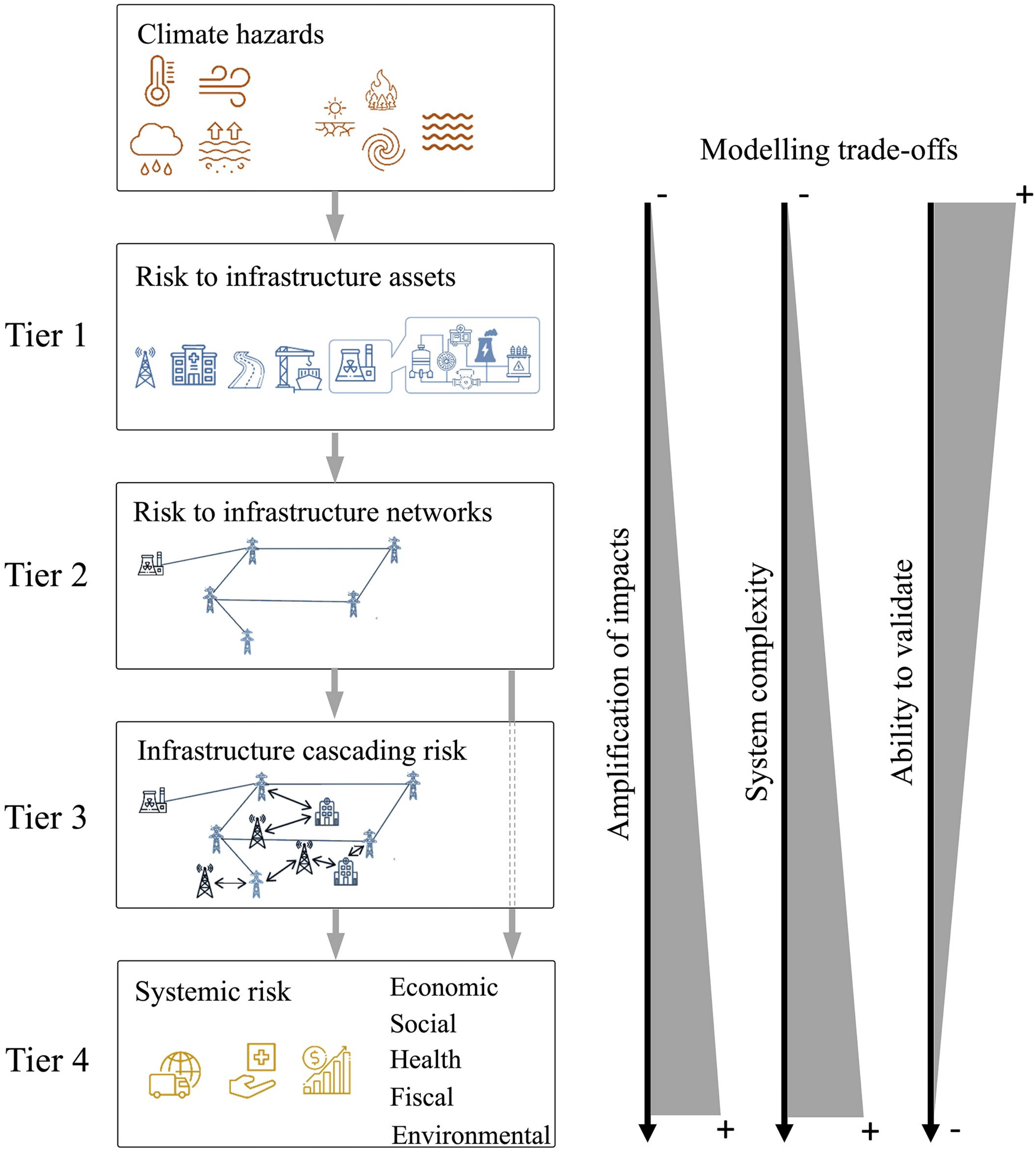

Fig 3. Four-tier framework of climate risks to infrastructure following Dawson et al. [17], including the three modelling trade-offs.

https://doi.org/10.1371/journal.pclm.0000331.g003

activity reliant on transport, which has been difficult to obtain and generalise beyond national scales. Moreover, systemic risk estimates from individual road or rail asset failures cannot be summed up due to network effects. Hence, systemic risk assessments of road and rail networks failures under climate change-driven hazards have been limited so far, and are much harder to validate compared to tier one and tier two studies.

Inland water transport

Infrastructures located at inland waterways (IWW), including navigation channels, locks and river ports, have received less attention compared to other transport networks. However, operations of inland water transport are particularly vulnerable to river level changes, as well as episodic events (cyclones, and riverine flooding) that can pose critical threats to IWW assets [34].

Against this backdrop, diverse research streams have been developed to link variability in relevant climate hazards to IWW operations. First, studies have evaluated how certain operational thresholds are surpassed because of climate variability and how downtime duration and frequency change due to climate change. Studies have particularly focused on trends in water levels [35–37], or how climate change can effects sedimentation rates [38, 39]. The second stream focuses on evaluating the economic implications of climate change on IWW transport, ranging from disruptions to trade [35, 40] to increases in transportation costs and prices [41].

There is considerable scope to expand on existing studies, in particular to more correctly characterise the vulnerability of IWW systems, as well as developing more accurate models of factors driving the operability of IWW transport associated with extreme low and high flows, and sedimentation (and their links to climate change). Moreover, there is potential for better understanding the dynamic deployment of vessels during periods of high or low flow, which are important for understanding the potential for rerouting of flows to road and rail [42].

Airports

Climate hazards can affect the airport infrastructure's structural integrity and operational performance. Although the aviation sector is known to be proactive in safety management and hazard identification, existing risk practices are often short-term and, as a result, do not always identify climate hazards as critical threats [15].

Research has focused primarily on the implications of different climate hazards on airport infrastructure and operational continuity [43–45], mainly investigation those climate hazards that have been observed historically, such as storms [43, 46], flooding [45], and extreme heat [47–49]. These studies, which are often focused on specific geographies, for example, Southern Europe [44, 50, 51], South East Asia [52], North America [47, 53] and the Caribbean [49], discuss the insufficiency of existing design standards address changes in the climate.

Lately, more comprehensive risk frameworks have been developed, e.g. [50, 51], which utilise regional climate model projections to assess the changes of climate hazard indicators across airports. Although more comprehensive, they often fail to consider the network failures or systemic risks. Scholars have only recently started to analyse the systemic implications of specific climate hazards on the global airline system [54]. However, there is limited research connecting airports as part of the wider system of infrastructure, despite evidence of indirect impacts originating from a failures of other systems, like the electricity network [55]. Similarly, limited studies discuss the level of resilience of airports to such cascading impacts or how risks can be transferred from airports to interregional transport corridors (e.g., by preventing regional freight flows for entering or leaving a region) [56]. In other words, compared to other infrastructure sectors, climate risk analysis for airports lag behind in terms of the quantification of systemic or network impacts to and from airport infrastructure.

Seaports

Climatic hazards, in particular sea level rise, high tides, and waves will affect virtually all seaports globally at some point in the coming decades [57, 58]. Studies evaluating the impacts of these climate hazards often distinguish between two event types. On the one hand, high probability-low impact events mainly affect the day-to-day operations of ports, with damages usually included in the yearly maintenance of assets. On the other hand, low probability-high impact events affect multiple ports on regional scales, causing more severe impacts to assets, operations and potential trade bottlenecks.

In the literature, three different research streams have emerged. The majority of studies evaluate the within- and across-year variability of coastal hazards (e.g., on a daily basis) and characterize their relationships with infrastructure damages and operational downtime. These approaches allow for incorporating climate change effects directly into the analysis, and have been performed for the impacts of waves on operations [59, 60], sea level rise on temporary flooding [61, 62], and wind-induced downtimes [63].

The second strand of research focuses on the evaluation of the main climate hotspots across port assets (but within a single port boundary) using a risk perspective. Some focus on the mapping of critical elements within port boundaries from a complex network approach [64], whereas others prefer to evaluate the fragility of certain elements [65, 66]. Here, the evaluation of climate change lags behind, with only some authors embedding climate change effects [64].

The third research strand focuses on the exposure of port assets and how impacts cause direct or indirect losses [67, 68]. This third strand allows for a more comparative analysis across a large number of ports, though inevitably losing contextual details. Recently, some studies managed to scale this up globally [58, 69] and even accounted for systemic risks alongside the inter-ports logistic chains [70]. Similar to airports, studies evaluating climate risks due to infrastructure interdependencies within or in the vicinity of ports are lacking, despite ports often being a hub for multiple infrastructure systems.

Telecommunication infrastructure

Telecommunications infrastructure consists of a wide range of terrestrial (fixed and wireless) and satellite assets [71, 72]. Different parts of the telecom system are prone to climate hazards. For fixed fiber networks, there is evidence to suggest that these assets can be susceptible to surface and sub-sea physical damage as a result of climate extremes, despite being submerged or buried. In terms of mobile cellular networks, there are a range of different damage states that can affect these assets when subject to climate hazards [73], including damage to (i) onsite backup electricity generation equipment, (ii) active electronic radio equipment, and (iii) other infrastructure assets necessary to provide normal service [74].

There is currently a large gap in the literature in terms of quantitative risk approaches, as our review only highlighted a very small number of climate risk analyses focused on telecommunication assets. Regional evaluations which consider telecommunication assets include one study assessing the infrastructure impacts from European coastal flooding [75], two quantifying US hurricane impacts [74, 76], as well as one global assessment highlighting coastal flooding and tropical storm vulnerability [77]. One key reason for this is a lack of consistent datasets to enable this analysis, as well as a more thorough understanding of how telecom infrastructure could be affected by climate hazards.

Water infrastructure

Water infrastructure has two key distinguishing characteristics in terms of its susceptibility to climate hazards. First, water infrastructure is subject to disruptions triggered by different climate hazards: droughts impact water availability at each source (groundwater, surface water) while flood and/or extreme winds can impact the conveyance and treatment infrastructure. Second, water infrastructure systems are often more local and less interconnected compared to other infrastructure types, offering limited system redundancy in case of disruptions.

Climate risk analyses to water infrastructure have also focused on multiple tiers of analysis (Fig 3). At the asset level, research has sought to expand the traditional approaches utilised for quantifying factors of safety and risks of failure. Examples include quantifying the impacts of climate change on dam failure risk [78] and modelling the effect of changing water quality under climate change on drinking water treatment plants performance [79].

At the network level, research has focused on the quantification of climate impacts and the benefits of adaptation options, in particular for urban water supply [80, 81], urban drainage [82, 83], and irrigation [84]. Within this space, water infrastructure research spearheaded the development of methods to analyse the impact of uncertain climate futures on infrastructure performance. Rather than assessing risks under a few, hand-picked climate scenarios, these approaches use large ensembles of time series to identify critical thresholds and compare investment strategies that are robust and adaptive in the face of future uncertainties. The methods, referred to as 'decision-making under uncertainty', have been deployed to assess water infrastructure risks, especially at network scales [85, 86].

Compared to other infrastructure, there are fewer examples of climate risk analysis of water infrastructure at larger scale (continental or global). Some have leveraged climate model projections to analyse climate risks to wastewater treatment plans to river floods across China [87], or used global water resource models to quantify drought impacts to utilities globally [88]. However, the risks arising from multiple climate hazards have been less explored, as most research to date has focused on single hazard risk analysis. Similarly, compared to other infrastructure sectors, indirect impacts, such as those to different income groups or to firms, have not been widely explored in the literature.

Social infrastructure

The education and healthcare sectors are vulnerable to a variety of climate hazards (see Fig 1), with the potential of prolonged disruptions to educational and healthcare services. Compared to other infrastructure sectors, the diverse, decentralized and interdependent nature of the healthcare and education sectors poses unique challenges for understanding and addressing climate risks [89, 90]. Research streams investigating the impacts of climate hazards on these sectors can be grouped into three categories: (i) asset risks to social infrastructures, (ii) operational resilience of the service provision, and (iii) societal risks revolving around public health and educational attainment.

Studies examining climate risks to buildings in the healthcare and education sectors across geographical scales and multiple climate hazards are scarce. Most studies have taken place in the Global North context. US-focused studies include the assessment of structural wildfire impacts on local schools and hospitals [22], hospital exposure to wildfires and coastal flooding at the county-level [91], and hospital exposure to hurricanes and sea-level rise along the East and South coast [92]. In Nepal, one study highlighted how the education and health sector is an integral part for the identification of critical infrastructure prone to rainfall-triggered landslides [93]. There is a persistent need for more extensive infrastructure layers for hospitals and schools [94], which is only partly met by recent harmonized global datasets for the health and education sector [20], which rely on open-source data that have a known geographical bias in terms of coverage.

Further, progress has been made in understanding the risks of climate hazards to operational resilience of the healthcare sector, and to a lesser extent, in the education sector. For instance, patient surge models, which evaluate operational capacity constraints after disaster incidences, play a crucial role in disaster preparedness and response [94].

There is a growing recognition that these sectors heavily rely on other supporting infrastructure. Evaluation of social infrastructure interdependencies on a single building level [95], on regional scales [96, 97] and on national scales [76] has enabled road-based accessibility studies of health sites and emergency services during climate events [98, 99] and network-wide hazard adaptation appraisals [100]. However, modelling frameworks capturing the operational recovery of healthcare and educational services after climate-related disruptions remain understudied.

On a societal scale, limited academic attention has been given to the risks which present and future climatic risk drivers might pose on educational attainment and the education sector as a whole. Similarly, the link between physical and operational risks of both sectors, social equity, and community resilience is still in its infancy [101], underlining the complexity to scale up climate risk analysis for this infrastructure sector.

Energy generation, transmission and distribution

Due to their complex nature and large spatial extent, energy generation, transmission and distribution (EGTD) systems are vulnerable to a variety of climate hazards. Climate change affects EGTD both directly (i.e., impact of climate on reliability) and indirectly (i.e., climate affecting energy demand), with different impacts on generating units and transmission/distribution grids.

Existing research on the climate risks to EGTD can be divided into three groups: exposure analysis, power flow modelling, and network interdependency modelling. Exposure analyses focus on threats faced by the EGTD assets across larger scales. Asset-level risk analyses are often based on probabilistic risk assessment frameworks, such as meteorological and hydrological risks to electricity generation facilities [102–104], and extreme wind impacts to transmission systems [105, 106]. Exposure analyses are often used as standalone methodologies to evaluate how different assets are at-risk to failures or inoperability from climate-related extremes, or used to inform power flow models, which is the second type of model framework.

Power flow models use the spatial grid configuration, position of the assets (generators, demand) and the physical properties of the system to assess system performance [107, 108], usually within an optimization framework. They tend to capture the operational implications of asset failures (from a system perspective) and the changing demand and generational mix. Complementing exposure analysis studies, power flow models can also be used to assess indirect losses in the system, including demand not served or customers affected [108, 109]. In particular, they can model the extent to which power flow can be rerouted when parts of the network fail or, when the network lacks the required capacity, can lead to cascading failure. Due to the computational cost and complexity, power flow models are often limited to local control zones (under supervision by one system operator), although larger-scale models that can simulate large interconnected systems also exist [110, 111]. However, application of climate risk analysis within interconnected systems are scarce.

The third type of modelling framework is interdependencies analysis of EGTD systems with other dependent critical infrastructure systems to better capture how failures may propagate [112, 113]. Yet, these are mainly network-based models, and therefore do not include complex system characteristics as in power flow models. On top of that, power failures lead to wide-spread economic and social disruption, which has been quantified by coupling spatial analysis of power failures with macro-economic models for the United Kingdom [114] and the United States [109], yet are not widely used.

Despite some of the recent innovations made, methodological and practical challenges still remain, in particular comprehensively assessing the societal impacts of large-scale blackouts on communities, considering the interdependencies between EGTD and other critical infrastructures, and the limited access (due to confidentiality) to outage data, which makes validation and calibration of risk models challenging.

Limitations and research gaps

Based on the review of the research covering the different infrastructure sectors, we have identified seven key research gaps within current quantitative modelling studies. These research gaps are not intended to be a ranking of the most important ones, but are merely cross-cutting themes that were identified.

Studies assessing multi-hazard risk interactions across interdependent infrastructure sectors are lacking

An increasing (though still limited) number of studies have expanded their risk framework to capture multiple hazards affecting infrastructure assets. Yet, understanding the compounding or concurrent impacts of multiple climate hazards to infrastructure systems is still in its infancy. How the occurrence of one or multiple hazards in space and/or time may interact with interdependent infrastructure systems, and can cause cascading impacts, is not well addressed in the literature, mainly given the complexity of the task [115]. Given the interconnected nature of infrastructure, it remains difficult to comprehend if individual risk studies are additive, given the high likelihood of double counting. In addition, interdependency-driven infrastructure failure cascades may further amplify disruptions. An infrastructure that is already stressed due to one hazard may be less resistant to a subsequent hazard, which requires a deeper understanding of the dynamic vulnerability of infrastructure systems [116]. In other words, when looking at climate risks to infrastructure from service perspective, the various failure pathways need to be accounted for within a formal risk analysis. Promising research endeavours are taking steps to close this gap, both at a city scale [117] and at a more regional scale [76, 96, 118].

Unrepresented climate hazards and infrastructure sectors

While most combinations of climate hazards and infrastructure (as identified in Fig 1) have been considered, there are still clear gaps in coverage. In terms of asset-level climate risk assessments, there is considerably less research for water infrastructure, telecommunication infrastructure, solid waste, inland water transport and social infrastructure (e.g., hospitals, schools). For water infrastructure, most climate risk analysis focus on catchment- or utility-scale water balance, while the physical infrastructure are rarely considered in one assessments. Similarly, climate risk analyses to telecommunication infrastructure are scarce, given a limited understanding of the geolocation of telecom assets, their service area, and how they are vulnerable to climate extremes. For solid waste, climate risk analyses were virtually absent from the literature. In all the aforementioned cases, the availability of geolocated infrastructure data and the highly contextualised nature of these infrastructure was identified as limitation. This therefore requires a better integration of national level datasets in open-source data platforms (like OpenStreetMap), as well as the classification of infrastructure utilising new data sources (e.g., based on global building footprint data).

In terms of climate hazards, analyses of the impacts of extreme high and low temperature on infrastructure are less prevalent, in particular given their different impact pathways compared to rapid onset hazards. On top of that, quantified risk analysis of wildfires and landslides are still at its infancy, despite some recent progress in performing quantitative infrastructure risk analysis to infrastructure [119, 120]. Still, our understanding how the occurrence of wildfires and landslides result in physical damages and operational disruptions is limited, making it hitherto difficult to move from exposure analysis to formal risk analysis.

Difficulties of scaling-up analysis across geographies

It remains challenging to scale up climate risk analysis to the Global South or to larger regional or global scales. Apart from the aforementioned scarcity of infrastructure geolocation data, it is challenging to make informed model decisions regarding the climate loads that infrastructure systems will be able to withstand across geographies. However, despite these differences to quantify physical damages (akin to engineering standards and designs), there are also similarities across geographies in terms of operations thresholds, which are more related to common environmental factors that can create operational disruptions.

Fig 4 summarises some of these operational thresholds for extreme wind, heat and cold across infrastructure sectors. For instance, crane operations in ports shut down between 15 and 22 m/s, at which airport may also face disruptions. At 30 degrees Celsius, electricity transmission and distribution systems experience difficulties as transformers require load reduction, while at similar temperature road tarmac can melt and rail lines may experience buckling. Power generation at places may face operational challenges at -5 to -15 degrees temperature, while at similar low temperature, black ice formation on road surfaces can cause closures. Although these operational thresholds may still differ across geographies, some of the ranges provided could be used as suitable starting point for operational risk analysis.

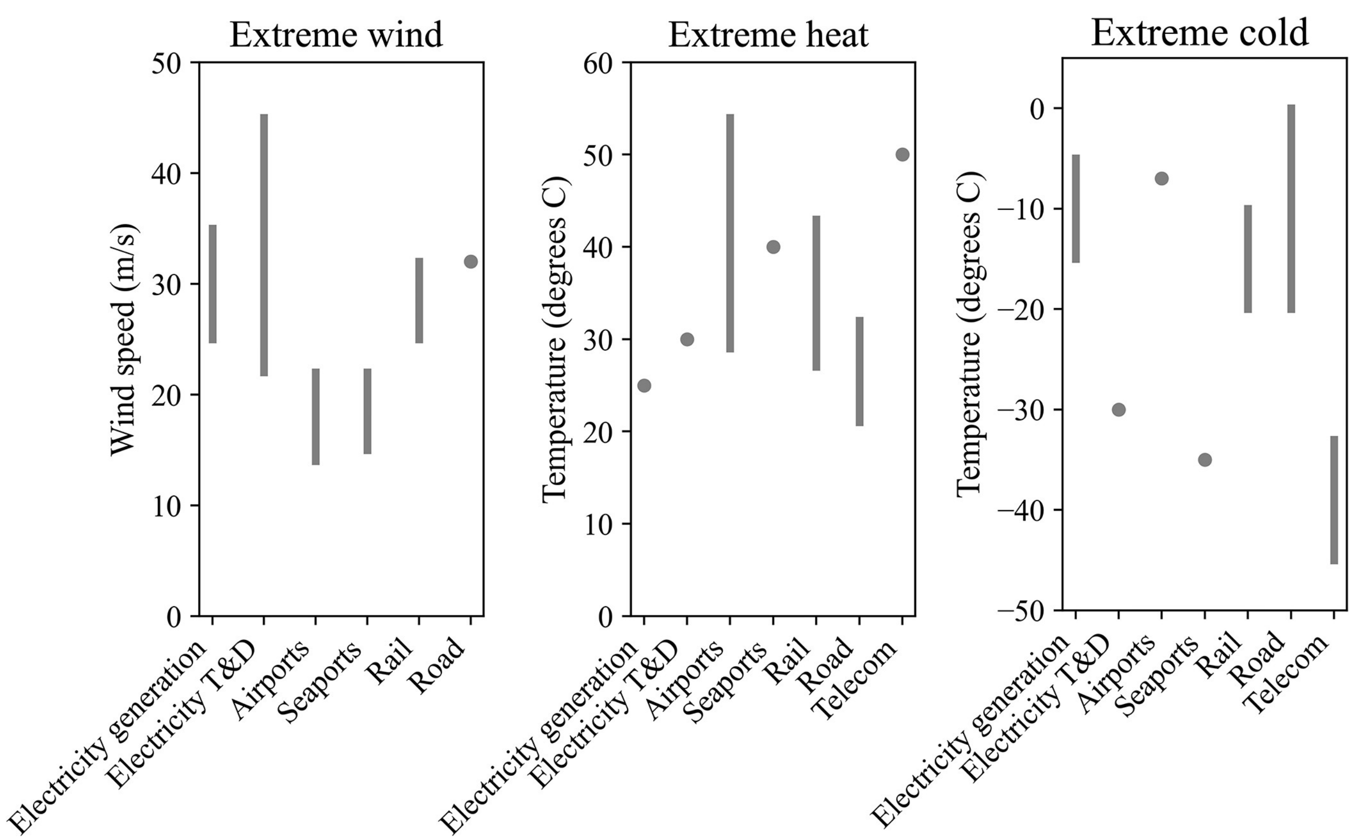

Fig 4. Overview of operational thresholds for extreme wind speeds, extreme heat and extreme cold temperature across infrastructure sectors. The bars indicate ranges provided in the literature while dots indicate an indicative value as mentioned in the literature. See S2 Table for further details.

https://doi.org/10.1371/journal.pclm.0000331.g004

The increasing need for validation data

The increasing complexity of modelling frameworks, especially in terms of scaling up spatially as well as incorporating more complex impact pathways (e.g., infrastructure interdependencies, cascading failures, societal losses), also requires more sophisticated validation data. However, validating these more complicated modelling components remains a major challenge across infrastructure sectors. First of all, if validation data after extreme hazard events is available, it is often not spatial (e.g., only the aggregate impacts). Second, it is hard to trace the impact channels of experienced disruptions after events, in particular those that originate from infrastructure interdependencies. Third, in reality, actions taken by actors within the different infrastructure systems (e.g., operators) already (partly) buffer part of the disruptions that could materialise (or amplify them in some cases), which are notoriously hard to model. This data validation gap requires researchers to work closely with infrastructure operators to ensure that relevant data is collected and/or monitored. However, recently some large scale validation datasets have occurred, e.g., for power outages [121], alongside other innovative or secondary proxy data could be used for such validation exercises, such as Nighttime Lights data to monitor electricity outages [122] and vessel tracking data to capture port disruptions [123].

Potential for knowledge spillovers across infrastructure sectors

Although the modelling frameworks of infrastructure sectors rely on similar data for climate hazards and asset-level fragility, different approaches are taken when it comes to impact modelling within infrastructure networks. As such, there remains scope for a better integration of approaches across infrastructure sectors, which may also help facilitate capturing dependencies across infrastructure systems. To find commonality between risk analyses across multiple sectors, two key focus areas should be considered. First, there is a need to create process-flow models that represent multiple infrastructure in a common way. For example, network model representations that optimise balance and redistribution of flow from generation sources (e.g. power plants, water intake points, origin ports) towards intermediate nodes (transmission substations, water treatment plants, transhipment ports) and finally to demand sinks (distribution transformers, water tanks, destination ports). Second, it requires identifying common disruption metrics such as numbers of customers affected or economic loss in monetary terms, which would allow comparison of risk metrics across multiple sectors.

Equity considerations of service disruptions

Infrastructure systems can amplify inequalities when affected by climate hazards. For instance, poorer households may (i) rely on more climate susceptible infrastructure or infrastructure systems with less redundancy [124], (ii) be deprioritized in restoration efforts [122], or (iii) lack the means to cope with infrastructure disruptions [125]. While these equity considerations have been recognised in the literature and supported by (limited) empirical evidence, e.g. [124, 126], they have not found their way into quantified climate risk analysis yet. These equity considerations are particularly acute for water, health, education and electricity infrastructure, which provide basic services for human wellbeing [125].

Quantifying a wider set of impacts metrics

Most quantitative risk assessments still focus solely on quantifying physical asset damages alone (Tier 1). While an increasing number of studies are focused on quantifying higher Tier impacts (two to four), these are still relatively scarce in the literature. In addition, infrastructure disruptions can cause a range of impacts that are often not quantified, such as injury or mortality associated with accidents during hazard impact to infrastructure, increases in travel time (and the economic loss associated with that) [127], environmental impacts (e.g., due to failure of wastewater treatment plant) [128], or social unrest (e.g., during large blackout events) [129]. Hence, quantifying a wider set of impacts helps in assessing the wider tangible and intangible impacts that infrastructure disruptions may cause, which would strengthen the business case for improving the resilience of infrastructure systems. Empirical evidence on these wider tangible and intangible impacts is required to facilitate their incorporation in future quantitative climate risk assessments.

Conclusion

Some of the recent hazard-induced infrastructure disruptions have underlined that current modelling approaches to quantify climate risks to infrastructure systems still struggle to reflect real-world complexities. In this review article, we attempted to present a stocktake of the literature that intends to capture climate risks to infrastructure systems within quantitative modelling approaches.

By bringing together a group of experts from across different infrastructure sectors, this paper intended to capture modelling innovations across infrastructure sectors within a single review paper, thereby providing a more holistic overview of the recent research developments, which can help foster cross-sectoral knowledge spillovers. We identify several overarching research gaps, which include (i) limited considerations of multi-hazard and multi-infrastructure interactions within a single modelling frameworks, (ii) scarcity of studies focusing on certain combinations of climate hazards and infrastructure types, (iii) difficulties in scaling-up climate risk analysis across geographies, (iv) the increasing challenge of validating models, (v) the untapped potential of further knowledge spillovers across sectors, (vi) the need to embed equity considerations into modelling frameworks, and (vii) quantifying a wider set of impact metrics.

We also highlight several opportunities to address the identified research gaps, thereby providing a shared research agenda for the wider research community. Most importantly, we hope that this review paper encourages further dialogue and knowledge sharing between researchers from different communities working on climate risk and infrastructure systems, given the truly interdisciplinary nature of the topic.

Supporting information

S1 Table. Overview of major recent events per infrastructure sector, including the physical damages and service disruption. The events are shown in Fig 2.
(DOCX)

S2 Table. Overview of operational thresholds for different combinations of hazards and infrastructure. The ranges/mean values are shown in Fig 4.
(DOCX)

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