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PAPER

Climate change hazards, physical infrastructure systems, and public health pathways

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Abstract

Climate-related hazards such as heatwaves, flooding, wildfires, and storms will increase morbidity and mortality unless infrastructure decision-makers—including urban planners, infrastructure asset managers, and utility providers—implement preventive measures to protect public health from these hazards. Existing research and policies have not systematically identified the key risk factors that these decision-makers need to manage to protect public health in a changing climate. This gap leads to unclarity regarding what infrastructure interventions are required to prevent climate-related health risks and what actors have a responsibility to manage these risks. The Climate-Health-Infrastructure-Pathways Model is introduced in this paper to address this gap and provide a conceptual map that captures the role of physical infrastructure systems in the pathways between climate-related hazards and health risks. The model surpasses what can be found in existing climate change research and policy, including the latest IPCC reporting, and is a conceptual qualitative tool that offers a typology of climate and health risks for infrastructure management. Decision-makers can use the model as a starting point to review the coverage of their current climate risk management plans and identify further opportunities to develop preventive infrastructure responses to protect public health in a changing climate.

1. Introduction

A growing body of epidemiological research demonstrates the threat of climate-related hazards to public health. A study by Rocque *et al* [1] summarizes existing systematic reviews on climate change and health, evidencing that climate-related hazards can lead to mortality, respiratory and cardiovascular morbidity, and other adverse health outcomes, including vector-borne, food-borne, and water-borne diseases.

The 2022 report of the Lancet Countdown on Health and Climate Change [2] recognizes that in addition to interventions such as early warning systems and health system strengthening, physical infrastructure interventions can also help protect public health in a changing climate. There are pockets of research in specialist areas, for example, climate change adaptation and epidemiological literature, that recommend the use of individual infrastructure interventions to reduce the health impacts of certain climate-related hazards. However, limited attention has been given to the systematic role of physical infrastructure systems in the pathways between climate-related hazards and health risks, which would help to signal how well infrastructure systems are being managed to prevent these health risks. Furthermore, there are no existing studies that provide a holistic understanding of the key infrastructure interventions that decision-makers can develop to prevent morbidity and mortality due to climate-related hazards.

The Climate–Health–Infrastructure–Pathways (CHIP) Model introduced in this paper maps the role of physical infrastructure systems as an intermediary factor in the pathways between climate-related hazards and health risks. There is much complexity in how infrastructure systems can influence whether climate-related hazards manifest in health risks at a local scale, and the CHIP Model is a response to this complexity. The purpose of this paper is to introduce the concept of the CHIP Model as the next step

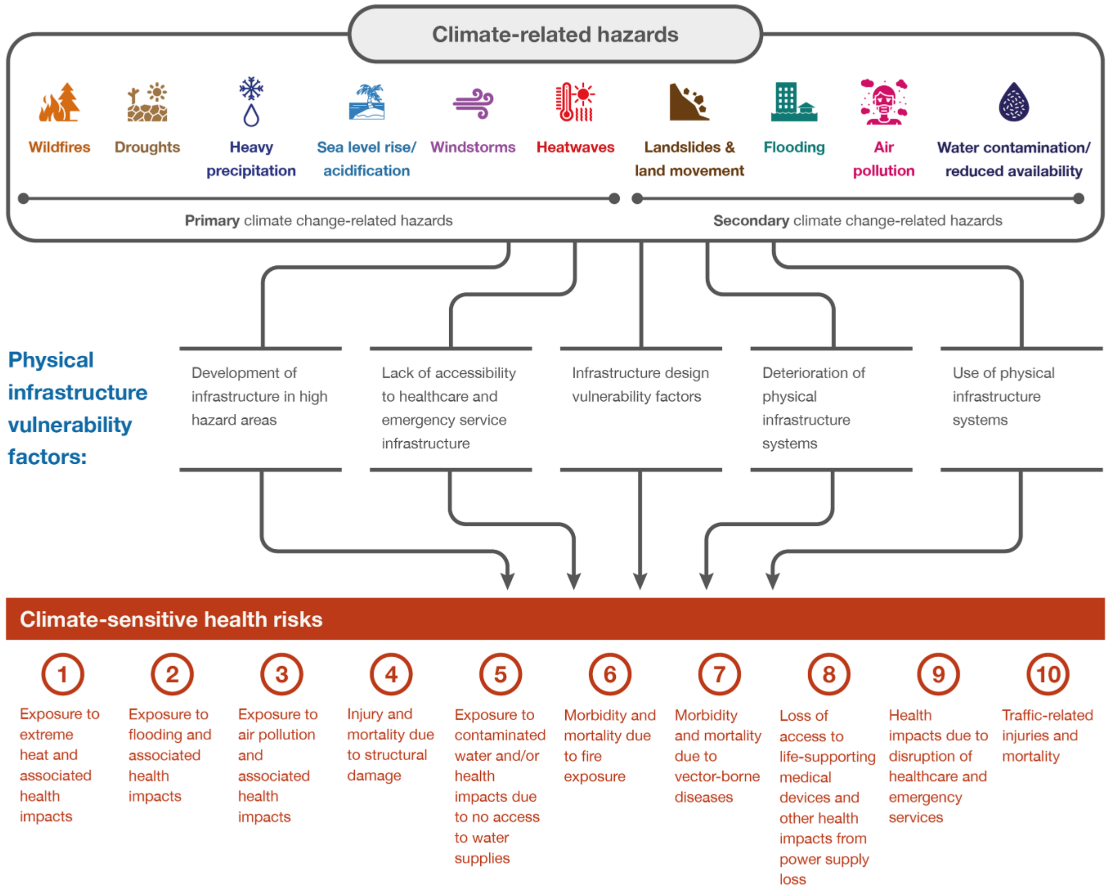

Figure 1. Conceptual Climate-Health-Infrastructure-Pathways Model.

forward in helping infrastructure decision-makers cross-check the coverage of their climate risk management plans and whether they include sufficient physical infrastructure interventions to protect public health from climate-related hazards.

2. Overview of the CHIP Model

The CHIP Model conceptually illustrates that the development, design, deterioration, and use of physical infrastructure systems can influence whether climate-related hazards harm public health. Figure 1 provides a high-level representation of the CHIP Model.

The CHIP Model was developed to provide a holistic understanding of the role of physical infrastructure systems in the pathways between climate-related hazards and health risks. This is because when it comes to assessing how well a region or city is managing climate risks given its climate and infrastructure, no one has presented a systemic view of the relevant physical infrastructure factors that influence exposure to climate-related health risks. The model captures a broad range of climate-related hazards and is based on varied cases from around the world, providing evidence of how physical infrastructure systems can influence whether climate-related hazards lead to health risks. The subsequent section of the paper describes the research methodology used to develop the CHIP Model. Section 4 then introduces the ten pathways that form the CHIP Model and offers evidence from existing literature for the physical infrastructure vulnerability factors captured by these pathways.

3. Methodology to develop the CHIP Model

The CHIP Model was developed through a review of multiple sources of literature and several steps, as shown in figure 2. An initial review of the recent IPCC Report Climate Change 2021: The Physical Science Basis [3], which is based on a comprehensive assessment of existing evidence on the physical science of climate change,

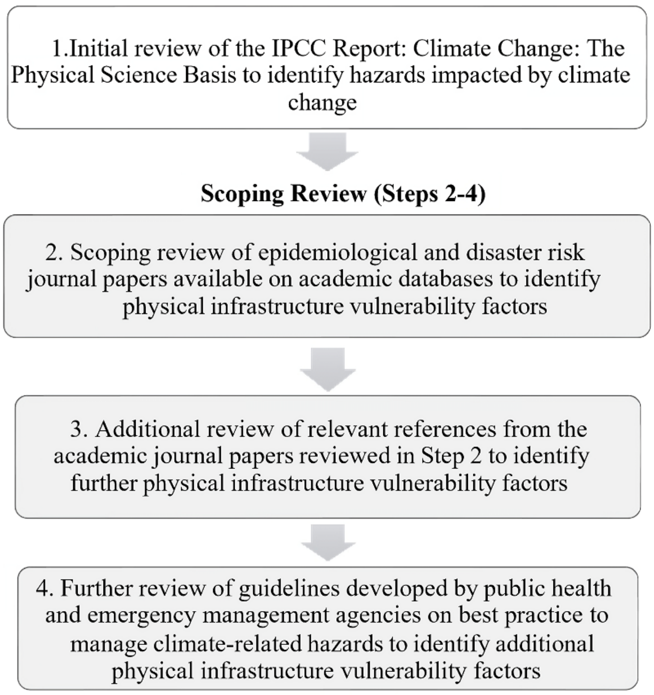

Figure 2. Literature review steps to develop the CHIP Model.

was used to identify how climate change will increase the frequency and severity of climate-related hazards such as heatwaves, flooding, droughts, and windstorms. The review of the IPCC report [p 864 and 1778] also helped to pinpoint that climate change can also impact air pollution, as well as water quality and availability.

A scoping review was then conducted to develop the CHIP Model. As suggested by Munn *et al* [4], a scoping review is appropriate to identify key factors or characteristics related to a concept. A scoping review was, therefore, a suitable methodology to help pinpoint a broad range of physical infrastructure vulnerability factors that influence whether climate-related hazards damage public health.

As a first step in the scoping review: a search of academic epidemiological and disaster risk journal papers available on the multidisciplinary databases: Scopus, Google Scholar, Web of Science, and Medline, was conducted. The search encompassed journal papers that were:

- Written in English language academic journals
- Published from 1 January 2005 to 31 March 2023

The search involved selecting each of the climate-related hazards identified through the review of the most recent report by the IPCC [3] (see Step 1), combined with the general risk, physical infrastructure, and health risk terms shown in table 1. For example, the keywords *flood AND risk AND/OR factor AND mortality* were used to help find studies that identify factors in the design of physical infrastructure systems that influence mortality due to flooding.

The titles of the articles identified through the initial search of academic databases were then screened. Articles with titles indicating modelling studies estimating future damage to human health due to climate-related hazards (with no mention of infrastructure) or titles suggesting a focus on non-human health risks were excluded at this stage. The abstracts of the remaining studies, whose titles indicated a link to physical infrastructure vulnerability factors influencing exposure to climate-related health risks, were then reviewed. Studies whose abstracts did not list physical infrastructure risk factors, for example, only listed demographic, socio-economic, or geographic factors, were excluded from a further review. A full-text review was then conducted to identify evidence of physical infrastructure factors that can influence health risks due to climate-related hazards. For example, a full-text review of the work of Jonkman *et al* [5] and Petrucci [6] helped to identify factors in the design of physical infrastructure systems that influence flood-related mortality.

A further review of references listed in the journal articles identified through the search of academic databases helped to find additional epidemiological and disaster risk journal papers that provide evidence of

Table 1. Example terms used in scoping review search to develop the CHIP Model.

Example key terms used in search						
Climate-related hazards:		General risk terms:		Physical infrastructure terms:		Health risks terms:
Flood OR heatwave OR windstorm OR heavy precipitation OR landslide OR drought OR air pollution OR water contamination OR sand and dust storm OR wildfires	AND	Risk OR vulnerability AND/OR factor	AND/ OR	Buildings OR infrastructure OR infrastructure disruption OR green infrastructure OR infrastructure planning OR infrastructure maintenance	AND	Mortality AND/OR morbidity OR health outcomes OR healthcare disruption

physical infrastructure factors that influence exposure to climate-related health risks. Since the aim of the scoping review was to pinpoint a comprehensive range of physical infrastructure factors, these studies were also used to develop the CHIP Model. For example, several studies in the initial search on *heatwaves AND risk AND factor AND buildings AND mortality* referenced the work of Bouchama *et al* [7], which provides a meta-analysis of factors, including infrastructure factors, contributing to heat-related mortality, and this study was therefore also used to help develop the CHIP Model. Furthermore, the review of references from the journal articles identified in the initial scoping review of academic databases also helped to find disaster case studies published by academic institutions, for example, a case study by the Australian National Climate Change Adaptation Research Facility [8] investigating the 2009 Australian Heatwave, that provide further evidence of physical infrastructure factors that contribute to climate-related health risks.

An additional review of English language guidelines, outlining responses to manage climate-related hazards, developed by major public health and emergency management agencies, such as the WHO, FEMA, and the CDC, and published on the websites of these agencies, helped to identify additional physical infrastructure factors that influence whether climate-related hazards lead to health risks. Since these guidelines can be based on comprehensive research and evidence gathered by public health and emergency management agencies, they were used as further evidence to help develop the CHIP Model and to ensure that it captures a broad range of physical infrastructure factors that can influence if climate-related hazards lead to health risks.

While the methodology used to develop the CHIP Model helped to capture a broad range of climate-related hazards and physical infrastructure vulnerability factors, the model can be expanded in future work. As outlined above, a review of the most recent report by the IPCC Report Climate Change: The Physical Science Basis [3], which is based on extensive modelling and research, was used to identify climate-related hazards that were then used in the search strategy for the scoping review. However, the CHIP Model can be expanded in future studies based on further scientific evidence, for example, from future IPCC updates, should they provide further scientific evidence of how climate change will impact additional climate-related hazards. In addition, the CHIP Model can be expanded in future work if a subsequent scoping review is conducted to identify new sources of evidence of physical infrastructure factors that can influence whether climate-related hazards damage public health, for example, from a review of journal articles published in languages other than English, review of additional academic databases, or of English language journal articles published after 31 March 2023.

4. The Climate-Health-Infrastructure-Pathways Model

4.1. Design pathways

The sections below provide an overview of the key design vulnerability factors captured in the ten pathways of the CHIP Model (see the supplementary material). These pathways include direct factors in the design of physical infrastructure systems that can influence whether climate-related hazards result in health risks. The pathways also capture design vulnerability factors that can lead to cascading effects due to climate-related hazards leading to the failure of physical infrastructure systems that can subsequently harm public health.

4.1.1. Pathway 1: exposure to extreme heat

Pathway 1 shows that the design of physical infrastructure systems influences the extent to which heatwaves damage human health, as evidenced by a growing body of literature. A study by Bouchama *et al* [7], which provides a meta-analysis of observational studies that have investigated protective factors during heatwaves, demonstrates that access to air conditioning can reduce heat-related mortality. A recent multi-country longitudinal epidemiological study by Sera *et al* [9] also shows that access to air conditioning reduces heat-related deaths. While air conditioning can reduce indoor temperatures in buildings, other active cooling measures, such as evaporative cooling and ground source heat pumps, can also be implemented at a building scale to reduce the exposure of building occupants to extreme heat. Furthermore, passive cooling measures can be adopted at a building scale to reduce high indoor temperatures and protect the health of building occupants. A study by Taylor *et al* [10] suggests that external shading can reduce heat-related mortality, and the WHO [11] also identifies that shading can help decrease indoor temperatures and protect building occupants.

While building-level measures can be implemented to protect public health during heatwaves, the design of physical infrastructure on an urban scale can also impact the extent to which the public is exposed to heat risk. There is evidence in existing research that the urban heat island (UHI) effect increases heat-related mortality [12–16]. However, measures can be implemented to reduce the UHI effect and protect public health from heatwaves. A recent study by Sera *et al* [17] shows that urban areas with a larger proportion of greenspaces have lower heat-related mortality than areas without green infrastructure.

Other factors in the design of physical infrastructure systems can influence whether individuals are exposed to extreme heat. For example, cooling infrastructure may fail if subjected to extreme conditions beyond its design parameters, leading to the loss of cooling and increased health risks during heatwaves. In addition, if power supply infrastructure systems are not designed to withstand extreme heat or to cope with increased power demand for cooling during heatwaves, this can result in power failure; if there are no redundant power supplies, this can lead to the loss of cooling and heat-related health risks. Several studies show that power supply loss during heatwaves increases heat-related mortality [8, 18, 19].

4.1.2. Pathway 2: exposure to flooding

Pathway 2 reflects that the design of physical infrastructure systems influences exposure to flood risk. The lack of flood protection infrastructure, including flood defences, drainage systems, or permeable surfaces, can increase the risk of flooding. Furthermore, if flood infrastructure does not have sufficient capacity, this can lead to damage to public health due to flooding. As shown by multiple disasters, including the Great North Sea Floods and Typhoon Hagibis, flood defence breaches can result in mortality and injuries [20, 21]. In the aftermath of Hurricane Katrina, neighbourhoods where levees were breached, and drainage systems failed, had the highest mortality [5].

4.1.3. Pathway 3: exposure to air pollution

The design of physical infrastructure systems can influence exposure to harmful levels of air pollution in a changing climate, as demonstrated in Pathway 3. For example, while climate change will increase the risk of exposure to wildfire smoke pollution, the design of built assets can influence the extent to which occupants are exposed to wildfire smoke. Buildings with less airtight envelopes have higher indoor wildfire smoke levels [22, 23]. As outlined in existing wildfire air quality guidance, reducing air infiltration in buildings can protect human health from wildfire air pollution [24].

Several existing studies also show that high-efficiency particulate air (HEPA) filters can lower indoor concentrations of fine particulate matter from wildfires [25–27]. The US EPA [24, 28] also identifies that portable air cleaners and high-efficiency filters can protect the health of building occupants from wildfire smoke.

Heatwaves can also impact air pollution levels, and there is evidence that higher temperatures increase surface ozone concentrations [29]. In addition, several studies suggest that high temperatures can increase particulate matter concentrations [30–32]. Since the design of physical infrastructure systems can contribute to ambient ozone and particulate matter air pollution, it is possible to change the design of physical infrastructure systems to reduce such pollution. For example, changing transport infrastructure design can help to reduce ozone and particulate matter concentrations, including during heatwaves. A field study by Anderson and Gough [33] also provides evidence that green infrastructure can reduce ozone concentrations, and the work of Maher *et al* [34] also shows that green infrastructure can reduce particulate matter concentrations. The design of built assets influences indoor air pollution levels and can help to protect occupants from exposure to air pollution in a changing climate. Research shows that active air filtration reduces indoor ozone concentrations [35, 36]. A recent systematic review by Wittkop *et al* [37] also provides evidence that air filtration can reduce indoor PM 2.5 concentrations and concentrations of inflammatory biomarkers associated with cardiovascular disease.

In addition, the IPCC [3, p 26] predicts that climate change will influence the frequency and intensity of sand and dust storms in certain regions. The design of physical infrastructure systems can influence the exposure of building occupants to air pollution due to these hazards. Filtered air conditioning or air purifiers with HEPA (PM2.5) filters can help reduce the exposure of building occupants to sand and dust particles which can harm human health [38]. Furthermore, a study by Yuan *et al* [39] shows that building envelope insulation can reduce indoor dust storm particle concentrations.

Climate-related hazards such as storms, flooding, and heavy precipitation can also increase indoor dampness and air pollution due to mould [40]. Several factors in the design of infrastructure systems influence whether building occupants are exposed to mould and associated indoor air pollution. For example, the provision of dehumidifiers can reduce the risk of indoor mould [41]. If built assets cannot withstand storms and heavy rainfall, this can lead to water ingress, which, as suggested by the WHO [40], can cause mould and indoor air quality risks. Furthermore, the lack of heating or adequate ventilation can lead to mould and indoor air pollution [40]. The lack of flood protection infrastructure can also contribute to the flooding of properties, which can also lead to mould and associated health risks.

4.1.4. Pathway 4: injury and mortality due to structural damage

Pathway 4 demonstrates that the design of physical infrastructure systems can influence whether climate-related hazards lead to structural damage of infrastructure assets and subsequent injuries and mortality. For example, creating safe rooms to withstand severe winds and installing storm shutters or storm-proof glass can help protect building occupants during windstorms [42]. Strengthening roofs and other built structures are further protective measures that can be implemented to prevent damage due to windstorms [42].

The structural design of physical infrastructure systems also influences whether landslides harm human health. Although landslides and subsequent damage to building structures can lead to injuries and mortality, certain building design features can make built assets more prone to collapse. A study by Pollock and Wartman [43] shows that variability in the construction materials used in built assets influences landslide mortality. In addition, the lack of property level measures, such as retaining walls, can influence whether built assets are damaged by landslides and lead to subsequent injuries and mortality [44, 45].

Floods can also lead to mortality from the collapse of building structures [5, 46]. Such damage results from physical infrastructure systems that have not been designed to cope with flooding and/or the lack of flood protection infrastructure.

4.1.5. Pathway 5: exposure to contaminated water or lack of access to water supplies

As shown in Pathway 5, the design of physical infrastructure systems influences whether climate-related hazards impact water availability and quality, which poses a risk to human health. The design of water-intensive physical infrastructure systems can increase the risk of disruption of water supplies in a changing climate. Furthermore, the deficient design of physical infrastructure systems can lead to contaminant run-off and subsequent water contamination, which can be impacted by climate-related hazards. For example, poorly performing wastewater systems can lead to nitrogen and phosphorus contamination into waterways, favouring the development of harmful algal blooms. This contamination can be exacerbated by warmer temperatures [47]. In addition, the lack of redundant water supplies can increase the risk of dehydration during heatwaves. As recommended by the WHO [48], the provision of water fountains can help to protect public health during heatwaves. The WHO [49] also suggests that the development of alternative water sources can help to ensure the safety and availability of water supplies in a changing climate.

Pathway 5 captures other factors in the design of physical infrastructure systems which may influence whether climate-related hazards impact water availability and the safety of water supplies. For example, the lack of flood protection infrastructure can lead to flooding of water infrastructure, which, as highlighted by the WMO [50], can increase the risk of water-washed and water-borne diseases. If water infrastructure is not designed to cope with climate-related hazards, such as extreme heat, this can also lead to water contamination or loss of access to water supplies, which can pose a risk to public health. Furthermore, the lack of soil stabilization infrastructure can lead to damage to water supply infrastructure which can also harm public health. There is, again an interdependency between the supply of power and the ability to supply treated water. If power infrastructure cannot withstand climate-related hazards this can lead to the disruption of water supplies, and as identified by the US EPA [51], such disruption can pose a risk to public health.

Pathway 5 may also be manifested through a climate-related hazard directly leading to water contamination. The provision of water treatment systems can help to prevent drinking water contamination and water-borne illnesses, including exposure to cryptosporidium and E. coli [52]. While the design of water treatment systems can influence water contamination levels, drinking water treatment facilities may not have been designed to cope with climate-related hazards and may have to be upgraded to prevent water contamination and subsequent health risks in a changing climate [49]. For example, while chlorination has been used to treat water to prevent water-borne illnesses such as cholera, it is less effective in treating certain water-borne pathogens, such as cryptosporidium, which can be influenced by climate-related hazards, and UV disinfection can be more effective in treating cryptosporidium [52, 53]. A study by Chhetri *et al* [54] shows that the installation of UV disinfection systems coupled with improved filtration in the Capilano reservoir, which supplies water to Metro Vancouver, Canada, helped to minimize cryptosporidiosis cases during extreme precipitation episodes.

Conventional water treatment (consisting of coagulation, sedimentation, filtration, and chlorination) is also not sufficient to remove high levels of cyanobacteria and/or cyanotoxins due to harmful algal blooms, and additional measures such as the use of microfiltration are more effective for their removal [55]. Furthermore, increased suspended solid loads due to climate-related hazards can lead to the need to adjust coagulation dosing to cope with such increases, and in some cases, water treatment facilities might not be able to support such demands depending on their design [56].

4.1.6. Pathway 6: exposure to wildfires

Pathway 6 illustrates that the design of physical infrastructure systems can influence the extent to which wildfires lead to morbidity and mortality. While residents are often advised to evacuate when their communities face wildfire risks, emergency services in some locations can also advise residents to shelter in place during wildfires. However, as shown during the Black Saturday bushfires, if built assets that shelter residents cannot withstand wildfires, this can lead to multiple mortalities [57]. As highlighted by FEMA [58], installing fire-resistant structural materials, fire shutters, and tempered glass can protect building occupants from wildfires.

4.1.7. Pathway 7: exposure to vector-borne diseases

As shown in Pathway 7, the design of physical infrastructure systems influences the extent to which building occupants are exposed to certain disease vectors that can be impacted by changing climate parameters. The WHO [59, p 5] highlights that the: 'entry of disease-transmitting vectors into human habitation can be effectively prevented by screening windows, doors, and eaves of houses, by fitting ceilings, and by reducing the vectors' indoor hiding and breeding places, such as cracks and crevices in walls, floors, and roofs.' A recent randomized controlled trial in Côte d'Ivoire also indicates that the installation of insecticide-treated nets coupled with insecticide-treated eaves tubes reduces the incidence of malaria [60]. As shown in a study by Che-Mendoza *et al* [61], insecticide-treated house screens can also reduce the abundance of aedes aegypti, a key dengue vector. A systematic review by Kua *et al* [62] summarizing existing evidence of how housing interventions impact vector-borne diseases shows that housing screening modifications, including the installation of insecticide-treated built environment features, lower the risk of malaria and aedes-transmitted diseases.

Other infrastructure design factors can also influence the spread of vector-borne diseases. For example, the presence of stagnant water increases the risk of certain vector-borne diseases, and the WHO [59, p 5] suggests that improving water and sanitation infrastructure to reduce sources of stagnating water and vector breeding sites, for example, by removing open gutters, can reduce the spread of vector-borne diseases.

4.1.8. Pathway 8: loss of power due to climate-related hazards

Climate-related hazards such as heatwaves, flooding, and windstorms can disrupt electricity services, which can damage public health. Previous extreme weather events show that blackouts can damage the health of individuals who use medical devices in a home setting, including individuals who rely on home oxygen therapy [63]. In addition, power outages, including due to extreme weather events, can lead to carbon monoxide poisoning and food-related illnesses [63].

Pathway 8 reflects that the design of power supply infrastructure impacts the continuity of power supplies in the presence of climate-related hazards. Power supply infrastructure systems that have not been designed to cope with climate change hazards, such as extreme heat, fail when exposed to such hazards. If there are no redundant power supply systems, this can lead to blackouts. Furthermore, the lack of flood or landslide protection infrastructure can lead to subsequent damage to power supply infrastructure due to these hazards, and if there are no redundant power supplies, this can also lead to power failure and associated health risks. As highlighted by Mango *et al* [64], improving the resilience of power supplies, such as the installation of battery storage, can help to protect public health, including the health of medically vulnerable populations in a changing climate.

4.1.9. Pathway 9: disruption of healthcare and emergency services

Climate-related hazards can disrupt the delivery of healthcare and emergency services, and as shown in Pathway 9, factors in the design of physical infrastructure systems impact on whether climate-related hazards lead to such disruption and subsequent damage to public health. For example, the lack of air filtration systems in healthcare facilities can lead to patient evacuations due to wildfire smoke [65]. Furthermore, if healthcare and emergency service infrastructure cannot cope with climate-related hazards, this can disrupt the delivery of these services. For example, if hospital HVAC systems cannot continue to perform during heatwaves, this can lead to a disruption to the delivery of healthcare services, including due to the closure of operating theatres in hospitals [66]. The lack of flood protection and soil stabilization infrastructure can also lead to damage to healthcare and emergency service infrastructure and disrupt the delivery of healthcare services.

Climate-related hazards can also damage the supporting physical infrastructure lifelines on which healthcare and emergency services rely, leading to cascading failure and disruption of healthcare and emergency services. If water infrastructure cannot withstand climate-related hazards or has not been designed to prevent water contamination, this can disrupt water supply to healthcare facilities and impact the treatment of patients. Allen *et al* [67] highlight that prolonged water supply disruption can lead to the closure of hospitals and other healthcare facilities. In addition, if power infrastructure is not designed to cope with climate-related hazards, this can cause disruption to the power supply of hospitals and impact on the delivery of healthcare services. Even if healthcare facilities have redundant power supplies, these are not always reliable and can be damaged by extreme weather events, as shown during Hurricane Sandy, when the failure of backup power systems at Bellevue and NYU Langone Hospital led to the evacuation of patients to other healthcare facilities [68]. In settings where healthcare facilities do not have redundant power supplies, the loss of electricity supplies can be catastrophic. For example, a study by Apenteng *et al* [69] highlights that power cuts for over two hours a day in Ghana resulted in a 43% increase in mortality in healthcare facilities. Climate-related hazards can also disrupt transport systems if they have not been designed to withstand these hazards, and this can subsequently disrupt the delivery of healthcare and emergency services. For example, if emergency transport routes do not have drainage systems that can cope with extreme precipitation, this can lead to flooding of key emergency transport routes and prevent ambulances from reaching hospitals.

4.1.10. Pathway 10: traffic-related injuries and mortality

Climate-related hazards influence traffic-related morbidity and mortality. Existing research shows that driving through floodwater is a major cause of flood-related mortality in countries such as the United States and Australia, where there is high car dependency [6, 70–74]. Furthermore, a systematic review by Petrucci [75] illustrates that landslides can lead to traffic collisions, injuries, and mortality.

As shown in Pathway 10, the design of physical infrastructure systems can influence whether climate-related hazards lead to traffic-related morbidity and mortality. For example, the installation of flood protection infrastructure can prevent road flooding and subsequent health risks. Furthermore, the use of soil stabilization infrastructure can help to prevent traffic accidents due to landslides.

4.2. Background physical infrastructure factors and exposure to climate-sensitive health risks

Pathways 1–10 in the CHIP Model capture key factors in the design of physical infrastructure systems that influence whether climate-related hazards damage public health. The development, deterioration, and use of physical infrastructure systems also impact whether climate-related hazards lead to morbidity and mortality. Therefore, these factors have been captured in the CHIP Model (see figure 1).

Firstly, infrastructure development in high climate hazard areas impacts the risk of exposure to climate-sensitive health risks. For example, the construction of physical infrastructure systems in floodplains, near the wildfire interface, or in areas prone to landslides or extreme heat can increase the exposure of residents to these hazards. In some cases, the scale of latent land-use factors may also limit the benefits of physical infrastructure measures that can protect public health. For example, a study by Ferdous *et al* [76] shows that increased urbanization in floodplains following the development of flood protection infrastructure can counter the benefits of such protection and lead to increased mortality.

The accessibility of healthcare and emergency service infrastructure can also impact the extent to which climate-related hazards damage public health. The time required for members of the public to reach a hospital following a severe medical incident influences their chances of survival [77]. A study by Nicholl *et al* [78] also shows that the distance to hospitals can impact patient mortality during emergencies.

The deterioration of physical infrastructure systems may lead to exposure to health risks in the presence of climate-related hazards. For example, climate-related hazards can exacerbate the deterioration of water supply infrastructure, which can compromise the safety and availability of water supplies. Deterioration of other physical infrastructure systems can also increase health damage from climate-related hazards. For example, inadequate maintenance of drainage systems contributed to the flooding due to Typhoon Ketsana leading to multiple mortalities [79]. The effectiveness of other infrastructure measures to protect public health from climate-related hazards, such as the use of air conditioning or air filtration systems, also depends on the condition of these physical infrastructure systems. For example, as outlined in a study by Iverson [80] investigating heatwave mortality records in Maricopa County Arizona from 2006 to 2016, 120 deaths occurred in indoor spaces where air-conditioning units were present but malfunctioning.

The use of physical infrastructure systems can also influence whether the public is exposed to climate-related hazards, and measures to change the use of physical infrastructure systems can help to protect public health in a changing climate. For example, restricting the use of road networks can reduce flood mortality due to drowning [81]. In addition to measures to restrict the use of physical infrastructure systems, changing their use, for example, by converting buildings to cooling centres, air quality, and storm shelters, can also help protect public health from certain climate-related hazards.

5. Summary

The CHIP Model demonstrates the role of physical infrastructure systems as an intermediary factor in the pathways between climate-related hazards and health risks. It is a conceptual model which captures that the development, design, deterioration, and use of physical infrastructure systems can influence whether climate-related hazards damage public health. By highlighting the role of physical infrastructure systems in these pathways, the CHIP Model provides a tool that can assist infrastructure decision-makers to explore the key risk factors for protecting public health in a changing climate in a systematic way. The CHIP Model surpasses existing research and policies, including the latest IPCC reporting, in terms of holistically reporting on these pathways and specifically framing the role of infrastructure in managing them. It provides a holistic conceptual model for infrastructure decision-makers to examine the scope of their current climate risk management practices and to develop preventive infrastructure responses to protect public health from climate-related hazards. Policymakers can use the CHIP Model as a conceptual tool for exploring the extent to which their infrastructure management and development activities are responding to the risk pathways most pertinent to their location. For example, through a review of the coverage of their climate risk management plans and if/how they incorporate physical infrastructure interventions. Decision-makers can also use the model as a starting point for exploring what further infrastructure interventions they can develop to protect public health from climate-related hazards, such as cooling and back-up power systems to reduce heat-related health risks. Future studies could expand the CHIP Model into a quantitative tool populated with data to model scenarios around the extent to which physical infrastructure systems are managed to protect public health in a changing climate. While quantifying all the interactions in the CHIP Model is a challenging prospect, quantitative methods, such as agent-based modelling, have existing capabilities to address aspects of certain pathways captured in the model.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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