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Title: Factors influencing vulnerability to climate change-related health impacts in cities – A conceptual framework

Year: 2023

Version: Published version

Please cite the original version:

Jurgilevich, A., Käyhkö, J., Räsänen, A., Pörsti, S., Lagström, H., Käyhkö, J., & Juhola, S. (2023). Factors influencing vulnerability to climate change-related health impacts in cities – A conceptual framework. Environment International, 173, 107837. https://doi.org/10.1016/j.envint.2023.107837

Environment International 173 (2023) 107837

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

Factors influencing vulnerability to climate change-related health impacts in cities – A conceptual framework

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ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
Climate risk
Health risk
Urban
Public health
Urban health
Pathway
Climate policy
Adaptation
Urban systems

ABSTRACT

Climate change will have adverse impacts on human health, which are amplified in cities. For these impacts, there are direct, indirect, and deferred pathways. The first category is well-studied, while indirect and deferred impacts are not well-understood. Moreover, the factors moderating the impacts have received little attention, although understanding these factors is critical for adaptation. We developed a conceptual framework that shows the pathways of climate impacts on human health, focusing specifically on the factors of urban environment moderating the emergence and severity of these health impacts. Based on the framework and literature review, we illustrate the mechanisms of direct, indirect, and deferred health impact occurrence and the factors that exacerbate or alleviate the severity of these impacts, thus presenting valuable insights for anticipatory adaptation. We conclude that an integrated systemic approach to preventing health risks from climate change can provide co-benefits for adaptation and address multiple health risks. Such an approach should be mainstreamed horizontally to all sectors of urban planning and should account for the spatiotemporal aspects of policy and planning decisions and city complexity.

1. Adaptation to health risks of climate change in cities

Climate change is likely to have significant adverse impacts on human health[A] (Smith, et al., 2014; IPCC, 2014). Studying these impacts is especially pertinent for urban areas as there are larger concentrations of people exposed to climate change risks (Revi, et al., 2014). More importantly, it is known that some forms of urban pattern and socio-economic activities increase citizens' vulnerability and exposure (Apreda et al., 2019; Sera et al., 2019).

The impacts of climate change on human health manifest through three pathways – direct, indirect, and deferred. *Direct* health impacts result from extreme weather events and are spatially and temporally proximal (Morris, et al., 2017). These impacts are well-known (Marsha et al., 2018), and are largely addressed through disaster risk management and other measures. Deferred and indirect risks of climate change on human health in cities are less understood (Morris, et al., 2017), and are mainly discussed in terms of systems thinking and cascading risks of climate change (Berry et al., 2018; Lawrence et al., 2020). *Deferred* risks result from the direct impacts but are temporally and/or spatially distal (e.g., post-flood mental stress or deferred morbidity after prolonged heat stress) (Smith et al., 2014; Morris et al., 2017; McMichael et al., 2012). Finally, climate change poses *indirect* risks[B] arising from climate-induced disturbances in the environment and inflicted upon human health through human-environment interactions (Smith et al., 2014;

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[A] Health is understood as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity"(WHO, 2020)(p.1). We approach health broadly as defined by the WHO and include also the impacts of climate change on maternal, foetal, neonatal, and occupational health.

[B] In our literature search and review, we approached health broadly, including both medically recorded and perceived health. We observe that regarding direct impacts, previous studies focused on medical recorded health, due to the possibility of attribution of health impact to a specific climate or weather event. Regarding the indirect and deferred impacts in observational studies, establishing reliable causation can be challenging. Therefore, studies reporting indirect and deferred impacts include both medically recorded and perceived health impacts.

https://doi.org/10.1016/j.envint.2023.107837
Received 29 September 2022; Received in revised form 27 January 2023; Accepted 16 February 2023
Available online 18 February 2023

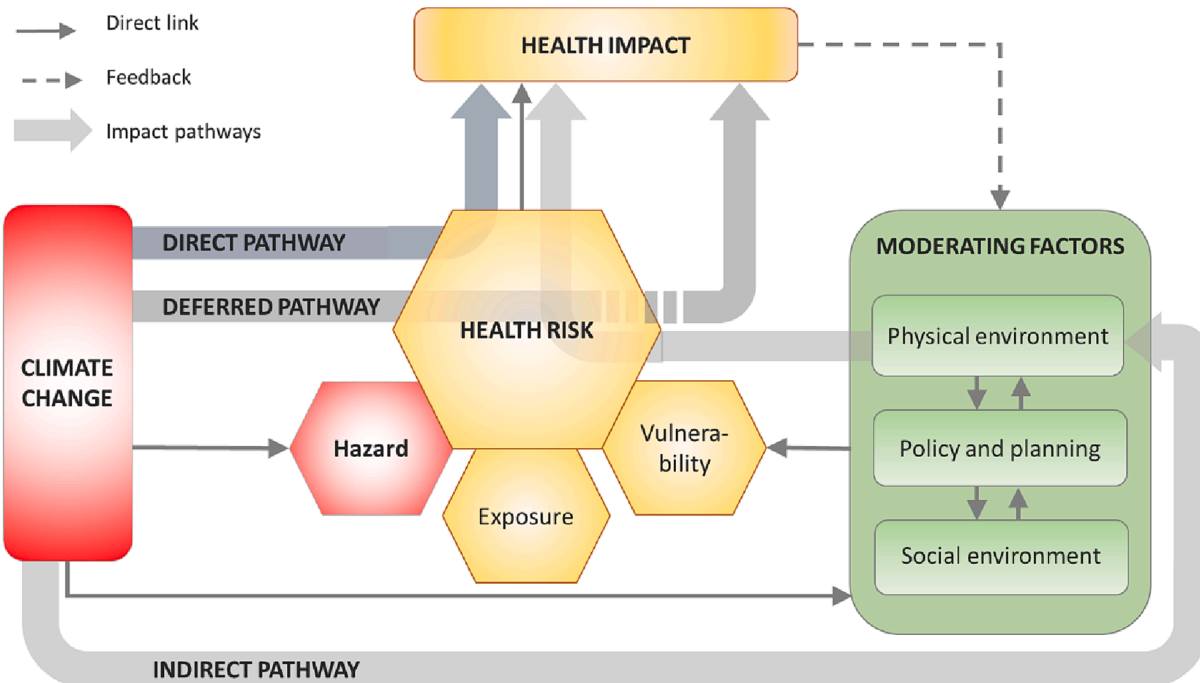

Fig. 1. Conceptual framework of the pathways through which climate change affects people's health (direct, indirect, deferred, based on (Smith, et al., 2014; Oppenheimer, et al., 2014; Galea and Vlahov, 2005), and of the factors moderating health risks and impacts. The moderating factors belonging to the three categories on the right moderate people's vulnerability to climate change-related health risks. It is pertinent to acknowledge that policy and planning category has influence also on hazards through mitigation policies, however, mitigation impact on hazards is postponed in time and space and contingent on the global mitigation efforts, thus a direct connection between policy and planning and hazard element is not illustrated. The three moderating factor categories do not exist in isolation but are in constant interaction and induce changes over time. Current physical and social environment are to a large extent a product of past policy and planning decisions. These factors moderate vulnerability in all three risk/impact pathways. The dashed arrow of deferred pathways illustrates that the impacts are postponed in time and space.

McMichael et al., 2012). Indirect risks materialise in impacts that can be both distal and proximal spatially and temporally, and include e.g., increase in vector- or water-borne diseases or diseases from worsened air and water quality.

Addressing these risks with anticipatory adaptation and urban planning in a strategic way is yet largely missing, resulting in fragmented adaptation, maladaptive outcomes, missed opportunities, and conflicts in agendas and resources (Sanchez Rodriguez et al., 2018; Reckien et al., 2019; Olazabal, 2020; Olazabal and Ruiz De Gopegui, 2021). This gap requires attention to conceptual development that treats cities as complex socio-ecological systems and examines the implications of urban change and system interdependencies (Egerer et al., 2021; Krueger et al., 2022). However, little attention has been paid to the urban environment factors that moderate vulnerability to climate change-related health risks, while risk assessments and policy decisions focus on hazards and separate sectors of urban planning (Crane et al., 2021). So far, there has been a call for tapping into urban sustainability transformations to improve health of urban residents, where integrated approaches and avoiding sectoral work in silos are key (Crane et al., 2021). In this article, we join this call and focus further on climate change-related health impacts. We suggest moving away from sectoral and hazard-specific risk assessments towards a more complex systems approach that considers dynamic processes and interdependencies within urban systems to support horizontally mainstreamed anticipatory adaptation and sustainable urban planning (Boyle et al., 2011; Rauken et al., 2015; Krueger et al., 2022).

In this review article, we illustrate the complexity of social-ecological interactions in urban environment causing health risks and examine the ways to address them. We reconstruct different pathways through which climate change can impact citizens' health in cities and focus our attention on the way urban environment, both social and physical, as well as policy and planning, shapes people's vulnerability to climate change-related health risks. Our rationale emphasises that these factors should be addressed with climate-resilient sustainable urban planning and anticipatory adaptation. We mobilize vulnerability, climate risk (Oppenheimer, et al., 2014), and urban/public health literature (Smith et al., 2014; McMichael et al., 2012; Galea and Vlahov, 2005), taking into account complexity theory and systems approach, (Berry et al., 2010). Thereby, we construct a framework that explains how climate change-related health risks emerge in cities, and what are the factors of urban environment that moderate citizens' vulnerability to them.

2. Conceptual framework of the factors influencing vulnerability to climate change- related health risks in cities

Our conceptual framework builds on the Intergovernmental Panel on Climate Change (IPCC) risk framing (Oppenheimer, et al., 2014) complementing it with health impacts, (Balbus et al., 2016) and different pathways of health risk emergence (McMichael et al., 2012) (Fig. 1). Climate risk is the potential of adverse impacts to occur and results from the interaction of hazards, vulnerability, and exposure[C] (Oppenheimer, et al., 2014). Exposure is the presence of people and assets in an area in which hazard events may take place, and vulnerability refers to the

[C] We acknowledge the differences in terminology in the fields of climate risk and epidemiology, specifically referring to differences in vulnerability and exposure definitions and concepts. In epidemiology, exposure is applied to any factor that is associated with the outcome of interest(Lee and Pickard, 2013), and vulnerability is defined and used heterogeneously, referring to the factors that increase the risk for adverse health outcomes and often focusing on personal factors (e.g., genetic pre-disposition), external factors (e.g., exposure) or social factors (social disadvantage or deprivation)(de Groot et al., 2019). While in some cases definitions and concepts are comparable in both epidemiology and climate change literature, we relied on the definitions of vulnerability and exposure in the framework, and in the review and analysis as presented in IPCC AR5 and AR6 WGII.

propensity of exposed people to suffer adverse impacts when exposed to a hazard (IPCC, 2022). Here, we approach vulnerability as a function of three elements: sensitivity (personal factors, such as age or pre-existing medical conditions), enhanced exposure (environmental factors, i.e., the extent the environment makes people more vulnerable to climate hazards), and adaptive capacity (social factors, i.e., capacity to prepare, respond and recover) (Kazmierczak, 2015; Lindley et al., 2011).

The framework explains how different impacts emerge, while focusing the attention on the moderating factors – factors of urban environment that affect the emergence and severity of climate-related health impacts, or more specifically exposure and vulnerability. While there are policies aimed at reducing hazards' severity, i.e., mitigation, their impact is postponed in time and space and is contingent on global efforts. Thus, to understand how urban environment, including policy and planning, shapes risks at the local level we focus on the factors influencing vulnerability and exposure.

A moderator is an external and independent factor that influences the strength of the relationship between an independent (here, climate change) and a dependent variables (here, health risks), i.e., explaining under what circumstances the relationship will hold (Baron and Kenny, 1986). These moderating factors are categorised in literature into 1) physical environment, including natural and built environment (local topography, urban infrastructure, green space, built environment, water and sanitation), 2) policy and planning (including health and social policies, adaptation and mitigation, urban planning), and 3) social environment (including social (in)equality, social strain, access to health and social services, resources, connectedness etc.) (Smith, et al., 2014; Galea and Vlahov, 2005) (Fig. 1). Both social and physical environment are influenced by policy and planning, and the moderating factors are often in a dynamic interaction with each other. Thus, the framework explains the relationship between climate change, urban environment, and human health through the delineation of impact pathways and categorization of factors, which should be seen through the complex and dynamic perspective.

2.1. Search and review methods

We used the existing primary and secondary literature, i.e., empirical articles and reviews respectively, to populate the framework with specific factors and impacts. Due to the differences in concepts and terminology of the fields we drew on – public health, epidemiology, climate risk, adaptation, and urban planning – a systematic search and review was not possible; thus, we relied on an iterative search strategy and snowball sampling. Based on the iterative search strategy, we *first* started with the key references used in the framework development to identify broader factor categories and impacts (Smith et al., 2014; McMichael et al., 2012; Galea and Vlahov, 2005). We searched literature with general queries ('climate' AND 'urban' AND 'health') and directed queries - specific hazards, urban, and specific impacts on human health (e.g., 'heat' AND 'urban' AND 'maternal health') using Scopus, Google Scholar, and Web of Science. Then, relying on snowball sampling principles (Johnson, 2014), we conducted new searches as new health impacts emerged from the literature.

Second, we analysed the literature with a directed approach (Hsieh and Shannon, 2005) using the pre-identified categories (physical environment, social environment, and policy and planning) in the identification of moderating factors; however, we did not consider the list to be exhaustive, and used the empirical literature to amend these categories. In the analysis, we 1) reconstructed the pathways of health impacts in cities relying on the conceptual framework (Fig. 1), and 2) populated the conceptual framework with the moderating factors.

We included the impacts that are both 1) climate change-related (induced or exacerbated by climate change), and 2) influenced positively or negatively by the urban environment. We, hence, excluded literature that deals broadly with the environment-induced risks to public health unrelated to or not exacerbated by climate change and irrelevant in or unaffected by the urban context (e.g., climate-related rural fleet or algae blooms impacts on health). In the analysis of factors, we focus on broader determinants of vulnerability at the population level, i.e., enhanced exposure and adaptive capacity (such as physical and social environment) as we are interested in the ways the urban environment shapes health risks stemming from climate change. The rationale of this focus is the possibility of reducing climate-related health risks through adaptation and urban planning; thus, we do not consider individual determinants of risks, i.e., sensitivity (such as age, health status or individual behaviours).

3. Factors moderating impacts of climate change on human health in cities

3.1. Direct impacts

Direct risks emerge from extreme weather events related to ambient temperature extremes, such as e.g., heat and heat waves, cold and cold spells, as well as storms and floods, and manifest in excess mortality, morbidity (incl. adverse impacts on maternal, foetal and neonatal health, and occupational health), and injuries (Table 1).

The factors moderating vulnerability to heat and heatwaves are related to *physical environment* (urban form, wind corridors, cooling surfaces, density of built environment, housing types, air conditioning, green infrastructure, e.g., green canopy), and *policy and planning* (building codes, social and healthcare services, urban planning, and adaptation) (Fig. 1). Summertime urban heat island (UHI) effect exacerbates heat and heatwave risks in urban areas due to compact settings and dependency on physical infrastructure (Ellena et al., 2020). UHI formation and severity is influenced by the density of built environment, urban form, wind corridors, cooling surfaces (highly reflective surfaces as well as green infrastructure), and green canopy (shading effect, e.g., (Salata et al., 2017; Venter et al., 2020; Arifwidodo and Chandrasiri, 2020).

The moderating factors of risks stemming from cold appear in all three categories (*physical and social environment, and policy and planning*), and include improved housing (with regard to age and materials to withstand cold temperatures), healthcare development, improved nutrition and overall welfare, building standards and housing, climate-controlled transportation and shopping facilities (Fig. 2) (Carson et al., 2006).

Overall, it has been suggested that physical environment influences vulnerability to both heat and cold extremes, and thus there is a co-benefit potential for anticipatory adaptation (Boyle et al., 2011; Gronlund et al., 2018).

With regard to floods and storms, some health impacts are inflicted directly by the hazard (drowning, hypothermia, acute anxiety), while others follow urban environment destruction or power outages (Table 2). The moderating factors belong to the *policy and planning category* and *physical environment* (Fig. 3). More specifically, vulnerability to the impacts of storms and floods (coastal, urban, river) is moderated by building codes, warning systems, disaster policies, evacuation plans, critical infrastructure management, and relief efforts (Greenough et al., 2001) (Fig. 3). In case of coastal cities, a managed realignment approach has been proposed (Plag and Jules-Plag, 2013). With regard to coastal floods or flash floods as a result of storms, local topography (*physical environment*) moderates the severity of the impact (Lane et al., 2013). Additionally, the severity of pluvial floods because of heavy precipitation is moderated by green and blue infrastructure, drainage systems, and surface permeability (*physical environment*) (Berndtsson et al., 2019; Sörensen et al., 2016).

3.2. Deferred impacts

Deferred impacts of climate change on health in cities manifest in mental health issues and chronic medical conditions postponed in time

Table 1
Pathways of direct impacts of ambient temperature extremes on human health in cities and evidence base supporting the risk/impact pathway.

Climate hazards	Health impact	Evidence base[a]
Ambient temperature extremes		
Heat		
Heat (number of degrees above the threshold or average value, excl. cold seasons) (Phung et al., 2016) [b]	Maternal health: eclampsia, preeclampsia, hypertension (Kuehn and Mccormick, 2017; Poursafa et al., 2015)	**Strong** Cohort studies, systematic reviews (Kuehn and Mccormick, 2017; Poursafa et al., 2015; Shashar et al., 2020)
	Neonatal and foetal health: Low birth weight, increased risk of still birth, preterm birth, and negative neonatal impacts (neonatal stress and mortality) (Kuehn and Mccormick, 2017; Carolan-Olah and Frankowska, 2014)	**Strong** Significant correlations regarding all the listed foetal and neonatal impacts (Kuehn and Mccormick, 2017; Poursafa et al., 2015)
	Occupational health: decreased productivity, dizziness, concentration decrease, reduced brain function, dehydration (Xia et al., 2018; Habibi et al., 2021; Kjellstrom, 2016; Kjellstrom et al., 2016)	**Strong** evidence on heat-related occupational morbidity and mortality, and productivity decrease among e.g., construction or municipal workers (Habibi et al., 2021; Kjellstrom, 2016; Kjellstrom et al., 2016)
Heatwaves (≥2 days of extreme high temperature) (Phung et al., 2016)	Increased mortality manifesting in preventable excessive deaths (Marsha et al., 2018; Anderson et al., 2018); increased cardiovascular disease (CVD) hospitalizations (Phung et al., 2016)	**Strong** Multiple empirical studies, e.g., during the heatwave in Europe in 2003 over 70,000 excess deaths were recorded (Robine, 2008) Systematic review and *meta*-analysis: significantly increased risk of CVD hospitalizations (Phung et al., 2016)
Diurnal variation in temperature (number of degrees between the lowest and highest temperature within 24 h) (Phung et al., 2016)	Increased morbidity manifesting in the significant increase in CVD[c] hospitalizations (Phung et al., 2016)	**Strong** Systematic review and *meta*-analysis: The risk of cardiovascular hospitalizations significantly increases with each degree (1 °C) increase in diurnal temperature (Phung et al., 2016); Significant association between diurnal temperature variation and cardiovascular mortality documented (Phung et al., 2016; Kan et al., 2007; Tam et al., 2009); Association between heat and CVD hospitalization in higher latitudes and colder climates (Turner et al., 2012)
Cold		
Cold and cold spells (number of degrees below the average threshold value and ≥ 2 days of extreme low temperature, respectively) (Phung et al., 2016)	CVD hospitalizations rate due to cold is higher than that due to heat (2.8 % vs 2.2 %, respectively) (Phung et al., 2016)	**Strong** Meta-analysis: significantly increased risk (2,8%) of cardiovascular hospitalizations (Phung et al., 2016)
	Adverse neonatal and maternal health outcomes: preterm birth, maternal hypertension, eclampsia, and preeclampsia (Poursafa et al., 2015)	**Strong** Systematic review (Poursafa et al., 2015)

[a] We assess the evidence base supporting the identified risk/impact pathways on the scale of tentative-moderate-strong based on the quantity and quality of existing studies. Strong evidence base builds on a well-established consensus on the pathways from climate hazard to health impact (e.g., systematic reviews, *meta*-analyses). Moderate evidence base builds on a larger number of empirical studies (>5), large datasets and studies that support the full pathway from climate hazard to health impact, as well as those cases where evidence is strong for the parts of the pathways, in case full pathway has not been in the focus. The evidence base is considered tentative when there are only few empirical studies (<5) or data is restricted.

[b] We draw on the definitions in (Phung et al., 2016). However, the duration and temperature thresholds with regard to both hot and cold ambient temperature vary in different countries.

[c] CVD itself is not always a primary cause for admission, but rather a pre-existing condition and a sensitivity factor, along with age (Phung et al., 2016).

after the direct impacts of storms and floods, as well as in deferred morbidity and mortality as a distal result of prolonged heat stress (specifically among outdoor workers, e.g., construction or municipal workers) (Table 3).

The moderating factors of deferred impacts of storms and floods include those that moderate post-traumatic stress disorder and other mental health conditions in the aftermaths of storms and floods. More specifically, there has been progress in identifying the indicators of vulnerability to post-disaster mental health outcomes (Foa et al., 2006; Hrabok et al., 2020; Kamal and Aslam, 2016), and how climate change and urban form exacerbate pre-existing mental health conditions, post-traumatic stress disorder and emotional stress in vulnerable populations (Greenough et al., 2001; Lane et al., 2013; Haney et al., 2010). These moderating factors are related to *physical environment* and include urban form (e.g., urban greenness, urban blue-green space, proportion of vacant lands, closeness to motorways, traffic and other environmental noise) (Babisch et al., 2014; Foley et al., 2017; Huang et al., 2016; Garvin et al., 2013) (Fig. 4). The moderating role of *planning and policies* on the relation between mental health and access to urban greenness is raised while evidence is not yet strong (Pope et al., 2018), and focus has been on the wellbeing impacts (see e.g., (Hiscock et al., 2017). Additionally, moderating factors related to *social environment*, such as marginalization and social (in)equality, have been pointed out (Lane et al., 2013; Adams and Nyantakyi-Frimpong, 2021; Hasegawa et al., 2015) (Fig. 4).

Deferred stress and anxiety resulting from the direct impacts of extreme weather events are associated with the increase in acute myocardial infarction (AMI) (Table 3) (Lane et al., 2013; Gautam et al., 2009). One study observed a threefold increase in AMI admission post-Katrina (Gautam et al., 2009). The data and results suggest that Katrina was associated with prolonged unemployment, loss of insurance, decreased access to health services, increased use of tobacco and substance abuse, leading to mental health problems, and resulting in the increased incidence of AMI. Additionally, post-disaster disruption in healthcare services was associated with the exacerbation of chronic health conditions, both physical and mental, as well as medical non-compliance and increased substance use disorders (Gautam et al., 2009). Overall, this suggests that moderating factors belong to *policy and*

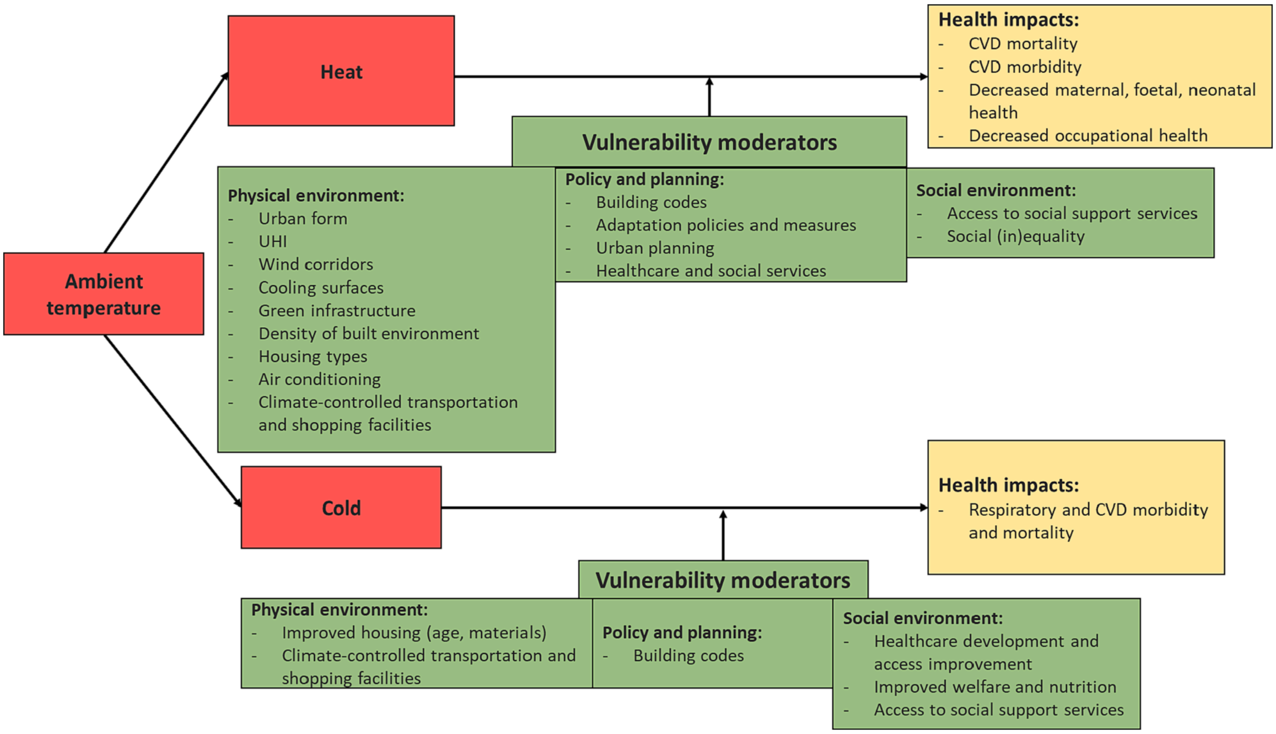

Fig. 2. Factors moderating vulnerability to the direct impacts of extreme ambient temperatures on human health in cities.

Table 2
Pathways of direct impacts of floods, storms, and related hazards on human health in cities and evidence base supporting the risk/impact pathway (evidence base is explained in footnote a to Table 1).

Climate hazard	Health impact	Evidence base
Floods (urban, river, coastal), storms and storm surges, local sea-level rise, and related hazards (Greenough et al., 2001; Lane et al., 2013; Adams and Nyantakyi-Frimpong, 2021)	Short-term health outcomes manifesting in mortality (drowning), hypothermia, acute anxiety Injuries from urban environment destruction and electrocution, hypothermia, acute anxiety (Adams and Nyantakyi-Frimpong, 2021; Plag and Jules-Plag, 2013; Lane et al., 2013)	**Strong** Multitude of reviews, empirical studies Drowning cases and injuries are often recorded by insurance companies, public authorities, hospitals (Greenough et al., 2001; Lane et al., 2013); qualitative empirical studies: perceived acute anxiety (Adams and Nyantakyi-Frimpong, 2021); reviews (Plag and Jules-Plag, 2013; Lane et al., 2013; Paterson et al., 2018)
	Illnesses, exacerbation of pre-existing conditions and increased morbidity/mortality in people dependent on electric medical equipment in consequence of power outages (Lane et al., 2013; Paterson et al., 2018)	**Moderate** Non-systematic review (Lane et al., 2013)

planning category, and include policies related to post-disaster relief, healthcare and access, employment, residence, and health and mental health counselling and support (Gautam et al., 2009) (Fig. 4).

Deferred impacts of prolonged heat stress are not well-studied. These manifest mainly in chronic conditions/deferred morbidity following occupational health impacts, resulting in chronic kidney disease (Tawatsupa et al., 2012), and neurodegenerative disease (Bongioanni et al., 2021) (Table 3). There is also tentative evidence on the association between overall higher mortality among elderly people with pre-existing conditions who have lived for a long time in cities with summertime temperature variability and lower percentage of green areas (Zanobetti et al., 2012). Chronic kidney disease is caused by prolonged dehydration, manifesting as a distal impact of prolonged heat stress, and increased incidence has been observed among manual outdoor workers (e.g., construction or municipal) (Tawatsupa et al., 2012). The moderating factors here are related to occupational health care intervention to reduce the adverse impacts of outdoor labour in heat (*policy and planning*), as well as those factors that moderate the direct impacts of heat (Figs. 5 and 2).

3.3. Indirect impacts

Indirect impacts of climate change on human health in cities manifest through worsened indoor and outdoor air quality, increase in vector-borne diseases, and medical conditions resulting from worsened water and soil quality caused by climate change and extreme weather events (Table 4). Outdoor air quality will likely be affected by climate change, including but not limited to the effects on ozone formation (especially by heat and UHI), spatial and temporal distribution of particulate matter (PM), changing the distribution and types of airborne allergens (Racherla and Adams, 2006, 2008; Kinney, 2018). Poor outdoor air quality may lead to the exacerbation of chronic respiratory diseases and

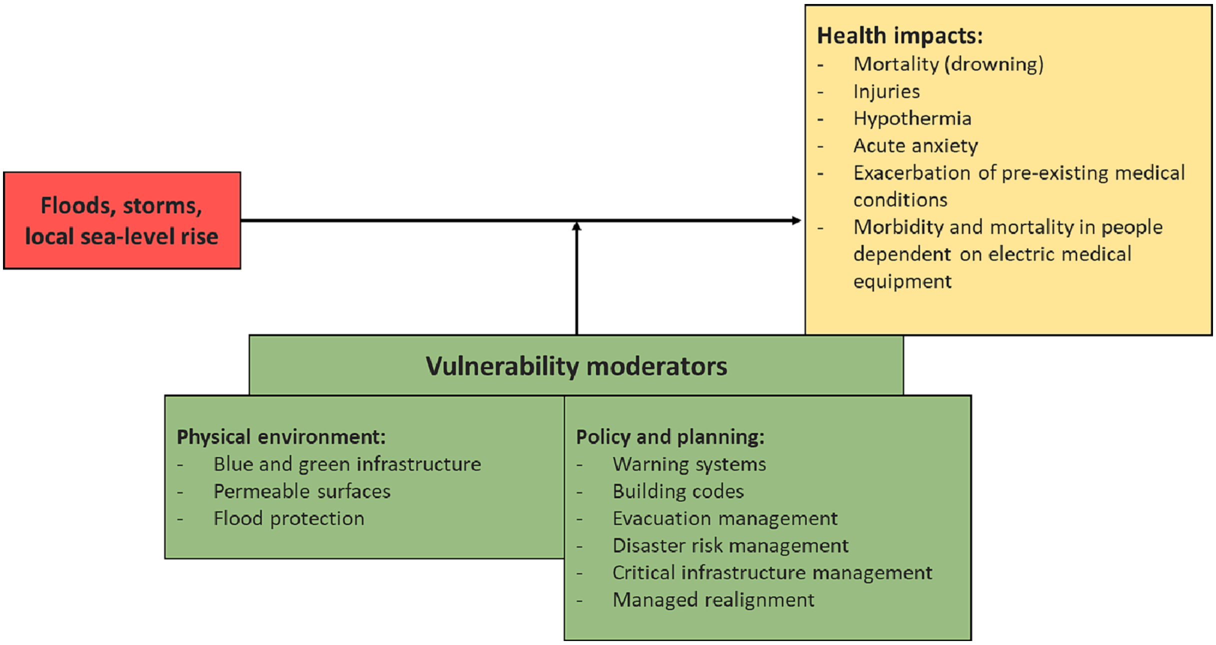

Fig. 3. Factors moderating vulnerability to the direct impacts of storms and floods on human health in cities.

Table 3
Pathways of deferred impacts of floods, storms, and heat on human health in cities and evidence base supporting the risk/impact pathway (evidence base is explained in footnote a to Table 1).

Climate hazard	Health impact	Evidence base
Floods and storms	Long-term outcomes on mental health from storm-related stress caused by residential destruction, displacement, and anticipation of flood re-occurrence (Lane et al., 2013; Adams and Nyantakyi-Frimpong, 2021; Gautam et al., 2009)	**Strong** Empirical studies of indicators of vulnerability to post-disaster mental health outcomes (Foa et al., 2006; Geng et al., 2018; Hrabok et al., 2020; Kamal and Aslam, 2016); qualitative empirical studies and reviews: climate change and urban form exacerbate pre-existing mental health conditions, post-traumatic stress disorder and emotional stress in vulnerable populations (Greenough et al., 2001; Lane et al., 2013; Haney et al., 2010; Kar et al., 2007)
	Exacerbation of chronic medical conditions (mental and physical) (Lane et al., 2013; Gautam et al., 2009); Acute myocardial infarction (AMI) following post-disaster decreased access to preventative health services, medication non-compliance, loss of insurance, prolonged unemployment, leading to chronic distress, and increased substance and tobacco abuse (Gautam et al., 2009)	**Moderate** Review, few empirical studies (Lane et al., 2013; Adams and Nyantakyi-Frimpong, 2021; Gautam et al., 2009)
Heat	Neurodegenerative disease (dementia of Alzheimer's type, Parkinson's disease, Motor Neurone Disease) following chronic heat stress (Bongioanni et al., 2021)	**Moderate** Review considering multiple climate change-related drivers and contextual factors (Bongioanni et al., 2021)
	Higher mortality among older people with predisposing diseases due to long-term presence in heat conditions in cities with summertime temperature variability (Zanobetti et al., 2012)	**Tentative** Time series in four cohorts' study, association lower in cities with higher percentage of green surface (Zanobetti et al., 2012)
	Chronic kidney disease due to prolonged dehydration (Tawatsupa et al., 2012)	**Tentative** Work-related prolonged heat stress correlates with chronic kidney disease (rural and urban cohort) (Tawatsupa et al., 2012)

reduced lung function due to the concentration of ground-level ozone, lung cancer (Hiatt and Beyeler, 2020), aggravation of chronic respiratory and cardiovascular diseases, damage to lung tissue and premature deaths due to particulate matter (Bernard et al., 2001), as well as have adverse effects on maternal, foetal, and neonatal health (Rylander et al., 2011; Jedrychowski et al., 2004; Lacasaña et al., 2005) (Table 4). Moreover, studies point out that the combined impact of heat and fine particles, i.e., PM2.5 has a greater effect on maternal health (Kwag et al., 2021) and CVD mortality (Ji et al., 2020), compared to the impacts of these stressors alone. Worsened indoor air quality transmitted from outdoor by air infiltration and ventilation systems causes similar impacts (Nazaroff, 2013; Salthammer et al., 2018; Vardoulakis et al., 2015). Additionally, storms and floods cause indirect impacts on human health through worsened indoor air quality, caused by the presence of harmful particles (e.g., moulds, endotoxins) from damp materials. These manifest in respiratory symptoms (e.g., asthma symptoms, rhinitis, rash, ocular and nasal symptoms), headache/dizziness, diarrhoea, stress, and anxiety (self-reported symptoms) (Hasegawa et al., 2015; Riggs et al., 2008) (Table 4).

The moderating factors of vulnerability to health risks associated with worsened outdoor air quality in cities are related to *physical environment* (urban form, type of pavement and roof materials, amount of tree canopy, wind corridors), and *policy and planning* (policies supporting cooling effect and air pollution control) (Fig. 6). The negative effects of climate change on air quality are especially pertinent for cities, since correlations between urban form, UHI and poor air quality have been documented (Stone, 2005; Kinney, 2008; Mika, 2018; Singh et al., 2020), and evidence-based suggestions regarding the improvement of urban air quality through physical urban planning have been presented (Stone, 2005). More specifically, cooling strategies have been suggested

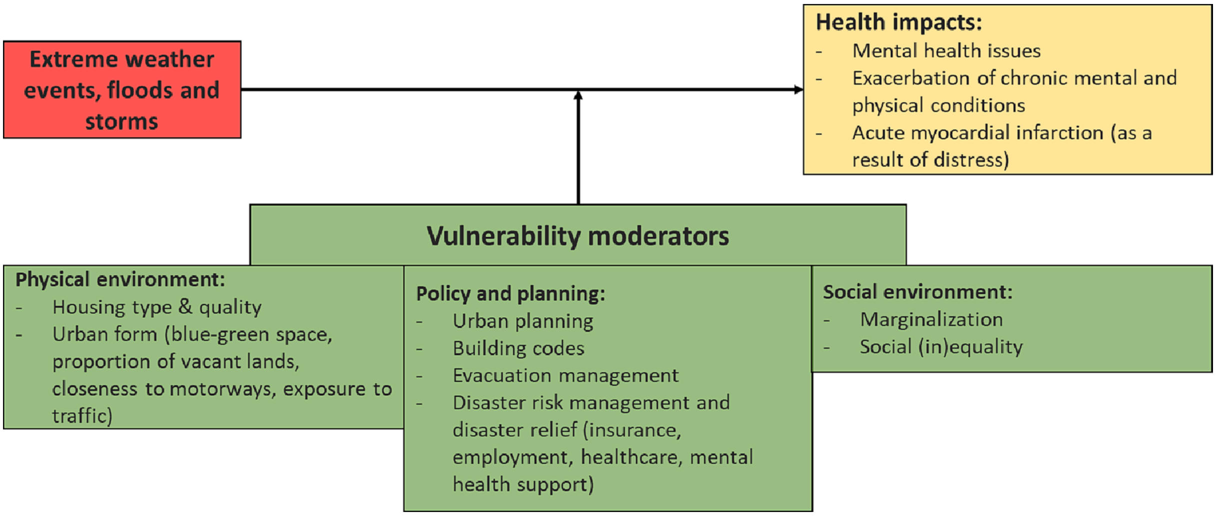

Fig. 4. Factors moderating vulnerability to the deferred impacts of storms and floods on human health in cities.

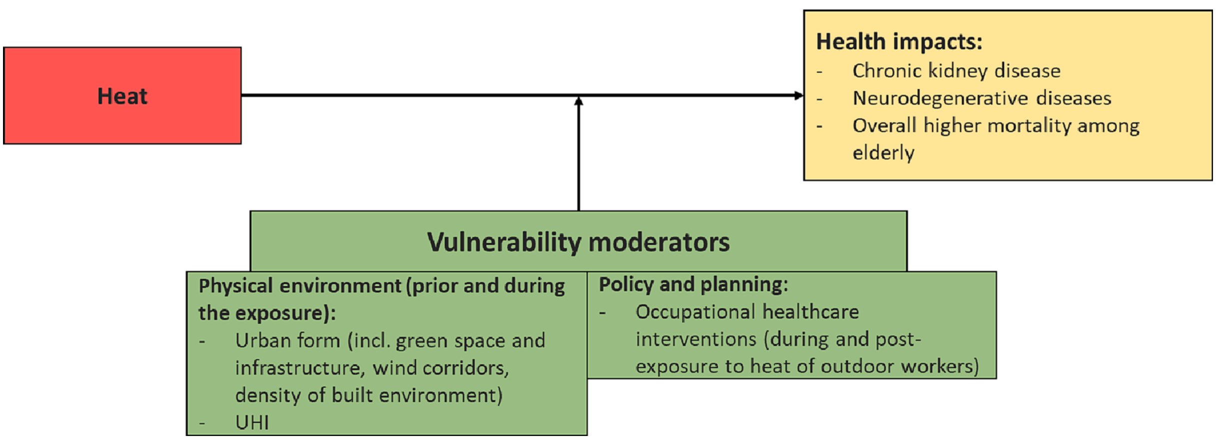

Fig. 5. Factors moderating vulnerability to the deferred impacts of heat on human health in cities.

to reduce the risks arising from urban air pollution, including the use of highly reflective paving and roofing materials, increase of tree canopy cover, and reduction of heat waste (Stone, 2005). Indoor air quality is affected by polluted outdoor air transmitted through ventilation and air infiltration systems (ozone and other pollutants), having similar health impacts (Table 4). Key moderating factors here are related to *physical environment* (building characteristics regarding infiltration and ventilation), and *policies and planning* (building codes, energy efficiency measures) (Nazaroff, 2013; Salthammer et al., 2018; Vardoulakis et al., 2015) (Fig. 6).

Extreme flooding events have indirect impacts on health through indoor air quality, more specifically, organic and inorganic air-transmitted particles from the damp or wet building materials (Nazaroff, 2013; Vardoulakis et al., 2015), causing respiratory symptoms for people living and working in flooded buildings (Table 4). Moderating factors here are related to building materials and height above ground level *(physical environment)* as well as building codes *(policy and planning)* (Fig. 7).

Extreme flooding events also impact water quality through stormwater as well as the release of hazardous substances and transfer of pathogens into drinking and ground waters in cases of sewage overflows (Lane et al., 2013; Paterson et al., 2018; Curriero et al., 2001; Charron et al., 2004). Associated risks include water-borne diseases (Greenough et al., 2001; Lane et al., 2013; Rose et al., 2000), respiratory, skin, and wound infections, chemical poisoning, and infections caused by different water-borne pathogens (e.g., gastrointestinal (GI) infections, leptospirosis) (Lane et al., 2013; Paterson et al., 2018; Fuhrimann et al., 2017). The moderating factors here are related to urban form (incl. local topography, permeable surfaces), flood protection, sewage system resilience and water treatment infrastructure (*physical environment*), as well as appropriate public health disaster response with regards to shelter, water, food, and sanitation (*policy and planning*) (Fig. 7) (Paterson et al., 2018).

Both extreme weather events and gradual changes affect food production conditions. Their adverse effects on human health via problems related to malnutrition is an emerging research topic (Swinburn et al., 2019) as is research on indirect risk pathways stemming from climate impacts in the urban context, such as urban sprawl overruling agricultural lands (Abu Hatab et al., 2019). Urban food production (e.g., urban farming) as an adaptation strategy is aimed at alleviating risks of food shortages and access to food, particularly in the developing cities (Padgham et al., 2015; Lwasa et al., 2015). Health risks are related to urban farming soil contamination by stormwater or hazardous substances (Padgham et al., 2015; Buscaroli et al., 2021), resulting in GI infections (Table 4) (Fuhrimann et al., 2017). Here, factors belonging to *physical environment* (state of/resilience of water system) moderate health risks, while malnutrition-related health problems are moderated via *social environment* (social inequality, access to nutritious food) in the first place (Fig. 7) (Dixon et al., 2007; Xu et al., 2019; Hashem, 2020).

Increase in vector-borne diseases has been associated with overall increasing temperatures in case of ticks, as well as water collection following heavy rains, local sea-level rise, floods, or storms in case of

Table 4
Pathways of indirect impacts of climate change on human health in cities and evidence base supporting the risk/impact pathway (evidence base is explained in footnote a to Table 1).

Climate change-induced disturbances	Health impact	Evidence base
Heat-related		
Outdoor air quality: Tropospheric ozone formation, particulate matter (PM) distribution (spatial, temporal), airborne allergen changes (types, distribution) (Bernard et al., 2001; Kinney, 2008)	Health effects of air pollution and poor air quality: exacerbation of chronic respiratory diseases and reduced lung function due to ground-level ozone, aggravation of chronic respiratory and cardiovascular diseases, damage to lung tissue and premature deaths due to particulate matter (Bernard et al., 2001), lung cancer (Hiatt and Beyeler, 2020)	**Strong** Extensive body of literature documenting negative effects of air pollution and poor air quality on human health (Hiatt and Beyeler, 2020; Bernard et al., 2001; Touloumi et al., 1997)
	Adverse impacts of worsened air quality (ozone formation, particulate matter) on maternal, foetal, and neonatal health (Rylander et al., 2011; Jedrychowski et al., 2004; Lacasaña et al., 2005)	**Strong** evidence on the adverse effects of PM and air pollution on neonatal and foetal health (Jedrychowski et al., 2004; Lacasaña et al., 2005)
Indoor air quality: external air-transmitted particles (ozone, PM) through ventilation and air infiltration (Nazaroff, 2013; Salthammer et al., 2018; Vardoulakis et al., 2015)	Same impacts as above (Nazaroff, 2013; Salthammer et al., 2018; Vardoulakis et al., 2015)	**Moderate** evidence, including non-systematic reviews and a few empirical studies on the features affecting vulnerability and exposure and health impacts of indoor air quality (Nazaroff, 2013; Salthammer et al., 2018; Vardoulakis, 2015) **Moderate** evidence on the link between climate change, indoor air quality and adverse maternal, foetal, and neonatal health (Rylander et al., 2011)
Flood-related		
Indoor air quality: internal air-transmitted particles from damp materials	Respiratory symptoms for people living and working in flooded buildings incl. restoration workers (perceived impacts highest during the first year after the flooding event) (Hasegawa et al., 2015; Rando et al., 2012; D'amato et al., 2010). Increased resident asthma symptoms, rhinitis, rash, ocular and nasal symptoms, headache/dizziness, diarrhoea, stress, and anxiety (self-reported symptoms) (Hasegawa et al., 2015; Riggs et al., 2008). Unhealthy levels of airborne moulds and other harmful organic matter (endotoxins, glucans) measured after one to two months of floods raised by hurricanes in U.S. (Rando et al., 2014; Riggs et al., 2008) and a tsunami in Japan (Hasegawa et al., 2015)	**Moderate** Empirical studies using large datasets, as well as analyzing the full impact pathway, e.g., respiratory health impacts of Katrina on people living and working in flooded buildings (Hasegawa et al., 2015; Rando et al., 2012; D'amato et al., 2010)
Water contamination with pathogens and hazardous substances due to stormwater and sewage overflows (Lane et al., 2013; Paterson et al., 2018)	Water-borne diseases (Greenough et al., 2001; Lane et al., 2013; Rose et al., 2000); respiratory, skin, and wound infections; chemical poisoning and infections caused by different water-borne pathogens manifesting in e.g., gastrointestinal (GI) infections, leptospirosis (Lane et al., 2013; Paterson et al., 2018; Fuhrimann et al., 2017)	**Moderate** Multiple empirical studies and non-systematic reviews Documented association between the outbreaks of water-borne diseases preceded by the increased precipitation; strongest association between the diseases due to surface water contamination within the month of an outbreak, and a two-month lag in cases of ground water contamination (Rose et al., 2000; Curriero et al., 2001)
Contamination of urban food production resources (soil, water in urban farming) (Padgham et al., 2015; Buscaroli et al., 2021; Li et al., 2018)	GI infections	**Tentative** Estimated risk of annual incidences based on measured organisms and pathogens (Fuhrimann et al., 2017), weather conditions compared with hospitalisation incidents (statistical data) (Lin et al., 2016)
Rising temperature + excess water		
Increase in vectors (ticks and mosquitos) as a result of overall temperature increase + excess water (e.g., inundation following a flood, storm surge, or local sea-level rise) (Plag and Jules-Plag, 2013; Menne et al., 2002; Magadza, 2000; Luber and Prudent, 2009)	Vector-borne diseases	**Strong** Multiple empirical studies and non-systematic reviews on the increase of favourable habitats and increase in vector-borne diseases in association with climate change (Plag and Jules-Plag, 2013; Luber and Prudent, 2009; Gray et al., 2009; Mathieu and Karmali, 2016; Karuppusamy et al., 2021; Moha et al., 2020; Ferraguti et al., 2016; Lyth et al., 2011)

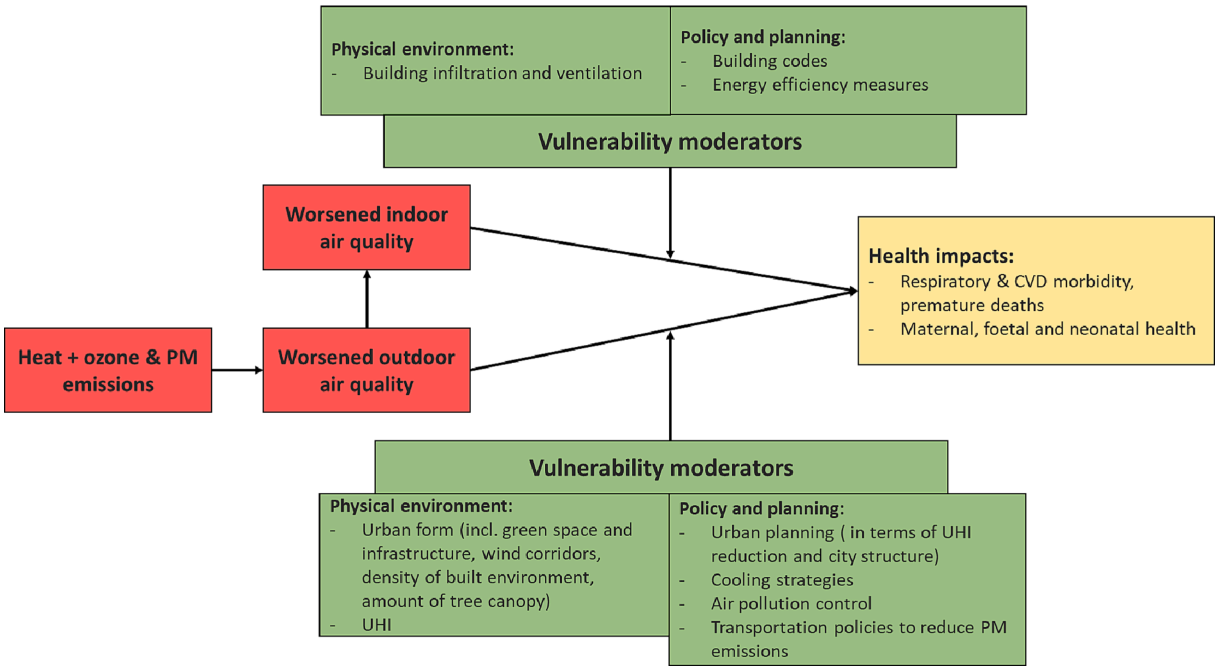

Fig. 6. Factors moderating vulnerability to the indirect impacts of heat-related worsened outdoor and indoor air quality on human health in cities.

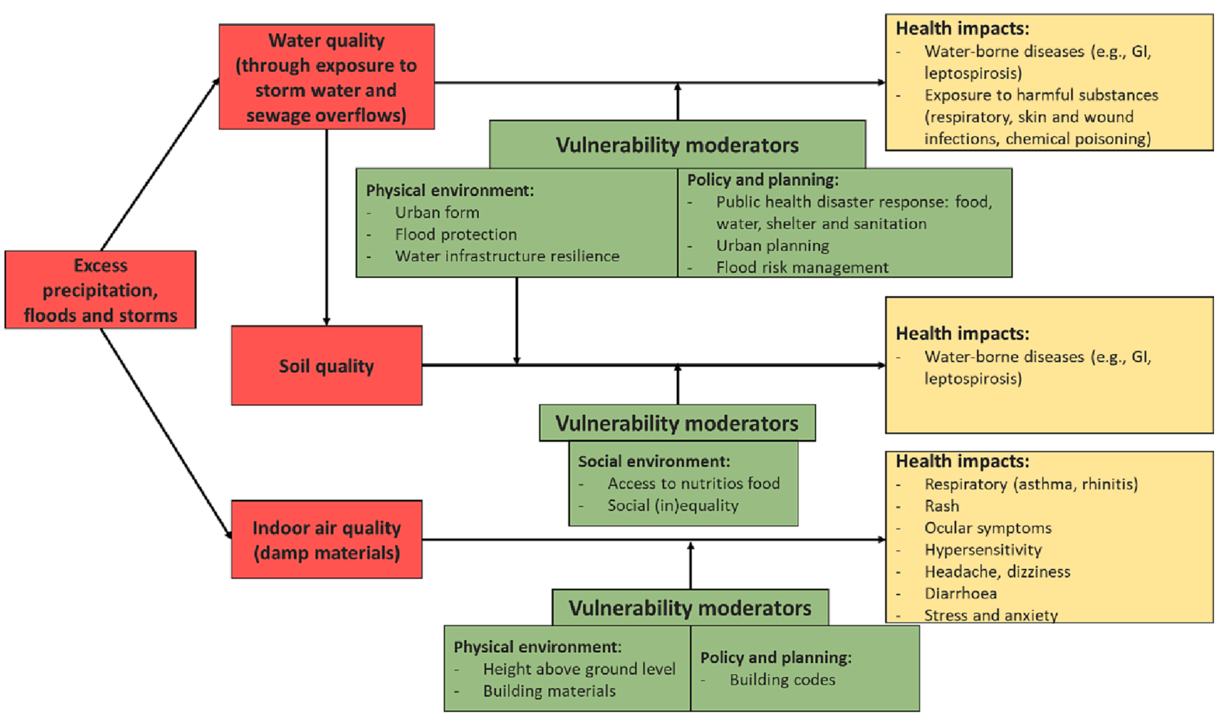

Fig. 7. Factors moderating vulnerability to the indirect impacts of excess precipitation on human health in cities.

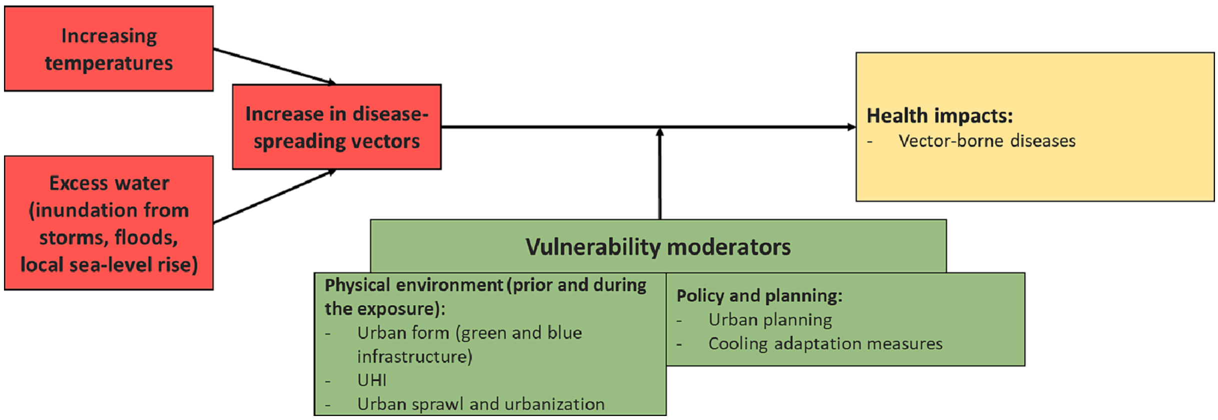

Fig. 8. Factors moderating vulnerability to the indirect impacts of increase in disease-spreading vectors on human health in cities.

mosquitos (Table 4) (Greenough et al., 2001; Lane et al., 2013; Paterson et al., 2018). It has been observed that urban form, e.g., water bodies, urban sewage systems, and subterranean and storm water systems, create favourable conditions for some species of mosquitos (Ferraguti et al., 2016). Urban sprawl has effects on land cover, local microclimate, and local habitat availability for vectors and their capacity (Mathieu and Karmali, 2016). More specifically, growth and behaviour of vectors is highly sensitive to temperature changes, which in turn are influenced by UHI, and urban areas are characterized by higher temperatures than surrounding rural areas. At the same time, efforts to mitigate urban heat island effects by creating more green and blue places such as parks and lakes could expand the habitat of mosquitoes and ticks, especially if combined with climate warming (Mathieu and Karmali, 2016). Thus, the factors moderating vulnerability to vector-borne diseases in urban areas are related to the *physical environment* (urban form, green and blue infrastructure, UHI, urban sprawl and urbanization), and *policy and planning* (urban planning, cooling adaptation measures) (Fig. 8).

4. Systems approach to reduce climate change-related health risks in cities

Our conceptual framework explains the pathways of climate change impacts on human health in cities focusing attention on the factors of urban environment affecting the severity of these impacts. Literature already shows that adaptation to health impacts planned solely by healthcare sector is insufficient (especially with regard to indirect and deferred pathways) (e.g., (Lane et al., 2013; Gautam et al., 2009; Negev et al., 2022), and that adaptation needs to take a preventative and systemic approach to reduce vulnerability and health risks (Negev et al., 2022). This includes mainstreaming adaptation horizontally to a variety of policy and planning areas, including housing, infrastructure and construction, urban planning, social and healthcare (Reckien et al., 2019) as well as recognizing trade-offs, co-benefits and possible maladaptive outcomes.[D] Overall, our argument is in line with the call for an integrated approach in urban sustainability transformations to address health risks (Crane et al., 2021), and this article highlights the potential of tapping into adaptation with a systemic approach.

The identification of moderating factors and connecting them with indirect and deferred impacts contributes to the planning and prioritization of adaptation measures in a sustainable and strategic manner. We observe that e.g., urban form is a factor moderating all types of impacts from both heat- and precipitation-related hazards. For example, green infrastructure and density of built environment have a moderating effect on UHI, exacerbating or alleviating heat risk. Urban planning efforts aimed at cooling effect such as more sparsely built environment, wind corridors, increased green canopy, have co-benefits for reducing health impacts caused by heat, exacerbated by UHI, as well as by worsened air quality. Thus, these efforts tackle multiple health risks, including direct heat-related risks such as CVD morbidity and mortality (Gronlund et al., 2018), deferred occupational health impacts (Kjellstrom et al., 2016), and indirect impacts occurring through worsened air quality (Kinney, 2018; Stone, 2005), as well as heat- and UHI-associated increase in vector-borne diseases (Mathieu and Karmali, 2016). With regards to vector-borne diseases, there is a certain trade-off in expanding green infrastructure, as while it provides cooling effects, it also enhances habitat for ticks, which needs to be anticipated and addressed with e.g., green area maintenance or awareness and vaccination campaigns to minimize maladaptive outcomes (Mathieu and Karmali, 2016). Overall, there are studies examining co-benefits of climate and health policies (see e.g., (Negev et al., 2022), but a systematic categorization of trade-offs, co-benefits and maladaptive outcomes is yet to be done. While this question has been out of the scope for this review, the identified moderating factors build ground for further work, and we recognize it as a pertinent issue for further research. Moreover, climate policy (including both mitigation and adaptation) is considered to have co-benefits for health beyond climate-related risks and can create policy alliances needed to steer sustainability transformations (Crane et al., 2021; Negev et al., 2022). For example, mitigation and adaptation measures related to green areas, also have co-benefits for physical and mental health and well-being (Negev et al., 2022). Similarly, mitigation efforts related to transportation, such as promoting carless mobility by creating cycling or walking infrastructure, have positive co-benefits for health and well-being (Giles-Corti et al., 2016).

The added value of examining different risk pathways from the perspective of adaptation co-benefits and sustainable urban planning is that by preventing and minimizing direct impacts, many of the deferred and indirect risks can also be averted or minimized. It is pertinent to consider the connections between these and direct impacts and factors in adaptation and urban planning. Deferred risks occur in the aftermath of direct impacts; thus, coherent prevention and timely response are critical. Similarly, some of the indirect risks following rapid climate-induced disturbances in ecosystems need to be prioritized. For example, well-functioning disaster warning systems and responses in cases of floods prevent not only immediate deaths and injuries, but also

[D] Co-benefit refers to a "positive effect that a policy or measure aimed at one objective has on another objective, thereby increasing the total benefit to society or the environment", trade-off to a situation when "a policy or measure aimed at one objective (e.g., reducing GHG emissions) reduces outcomes for other objective(s) (e.g., biodiversity conservation, energy security) due to adverse side effects, thereby potentially reducing the net benefit to society or the environment"; and maladaptation to "actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas (GHG) emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future" (IPCC 2022, p. 2904, 2915, 2925).

lower deferred mental health risks and deferred morbidity in the future (Gautam et al., 2009). Similarly, adequate disaster relief providing shelter, food, water, and sanitation helps minimize indirect risks through contaminated water and food (Lane et al., 2013). Overall, long-lasting disaster relief support that also includes social services, employment facilitation and insurance, contributes to the long-term well-being of those affected (Gautam et al., 2009).

These examples illustrate how the emergence of climate change-related health risks in cities is affected by policy choices across a number of sectors, stressing the need to address climate change also outside of the environment and health policies (Sanchez Rodriguez et al., 2018; Negev et al., 2022). Additionally, moderating factors are nested in a dynamic and complex system that a city is. These factors are in constant interaction with each other and can produce different outcomes. Thus, one should be aware of potential trade-offs and maladaptive outcomes. For instance, some studies have pointed out that the use of air-conditioning as an adaptation measure to reduce indoor heat stress may trigger large energy consumption, conflicting with mitigation efforts, worsen outdoor heat stress and put uneven economic burden on households, deepening and highlighting the problems of social and economic inequality (Viguié et al., 2020; Ortiz et al., 2022). Similarly, urban farming as an adaptation measure to combat climate-induced malnutrition can potentially mediate pathogens in case the soil is contaminated by storm water or sewage overflows (Padgham et al., 2015; Buscaroli et al., 2021). Flood protection measures preferred in the past (e.g., "hard" storm defences) are increasingly considered as maladaptive and replaced with "soft" measures such as managed realignment approach (e.g., in Southeast England and Netherlands) due to higher social and ecological sustainability (Shih and Nicholls, 2007; Esteves and Williams, 2017). Overall, current physical and social environment is a product of past policy and planning decisions; thus, in adaptation and in urban planning, temporal aspect as well as systemic connections should be taken into account to ensure sustainability of solutions, as was also suggested by Crane et al. (Crane et al., 2021).

Finally, several sensitivity and adaptive capacity factors have been mentioned as important for many impacts. Studies have mentioned that pre-existing medical conditions (e.g., CVD) make people more vulnerable to all types of ambient temperature-related impacts (e.g., (Phung et al., 2016). Similarly, broader socio-economic determinants have been pointed out as factors moderating the severity of flood, cold and heat risks (e.g., healthcare provision and expenditure, overall level of economic development) (Healy, 2003). This means that there is a broader need to address both health and social inequality to prevent already more vulnerable people suffering from the adverse impacts of climate change (Leichenko and Silva, 2014; Salm et al., 2021; Rahman et al., 2019).

In the search and review process, we have encountered several impacts for which the evidence is scattered or almost absent, but which are relevant for the urban context. Drought, and specifically urban drought, is known to cause water insecurity for urban populations, which are often dependent on the water sources outside the city (Wang et al., 2020). Multiple reviews point out drought and water insecurity to be a threat to public health; however, specific health impacts need to be studied further (Hoekstra et al., 2018). Another example is slipperiness, which is projected to increase with warmer and rainier winters in e.g., (Freistetter et al., 2022) Nordic countries, causing increased risk of injuries (Lépy et al., 2016) and road accidents (Andersson and Chapman, 2011). The evidence is emerging and the impact pathway as well as moderating factors need to be studied further to provide insights for adaptation and planning. Finally, it is pertinent to consider the slow-onset impacts of climate change (Adamo et al., 2021), e.g., sea-level rise or chronic heat stress (Oppermann et al., 2021), which are relevant for the urban context but evidence is yet scarce.

To conclude, in this review we have outlined the moderating factors of vulnerability to direct, indirect, and deferred impacts. We highlight how some of the moderating factors are relevant for several risks, and thus we see co-benefits for urban planning and adaptation. Additionally, we see that by managing some of the direct risks, we can also reduce indirect and deferred risks. We see the development in the scientific community towards systems approaches in adaptation, urban planning, and urban sustainability transformations (Crane et al., 2021; Negev et al., 2022), and we join this development bringing climate change perspective and adaptation possibilities. Similarly, Egerer et al. (Egerer et al., 2021) suggest tapping into urban change as an opportunity to improve adaptation to climate change. In this review, we observed the interconnections of different factors and especially the influence of policies and planning on both social and physical environment; thus, not only systems approach but also temporal dynamics needs to be taken into account. For this knowledge to be taken further conceptually as well as for its application in practice, further investigation and development of usability and compatibility of such approaches with urban governance structures and planning processes is needed.

Author contributions

All authors have contributed to the manuscript conceptualization and design. AJ and JK have collected and analysed the data. Manuscript writing was led by AJ with contributions from all authors to the manuscript writing, editing, and revising.

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.

Acknowledgements funding and conflict of interest

This article is a part of the "HERCULES" project funded by the Academy of Finland within the programme "Climate Change and Health" (CLIHE). The authors declare no conflict of interest.

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