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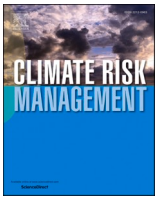

Measuring community heatwave resilience: A comprehensive framework and tool

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ABSTRACT

This article presents the first comprehensive, multi-sector heatwave resilience measurement framework and associated tool, available for use at the community or city neighbourhood scale. The question of how to live in a rapidly urbanising, climate change impacted world with more frequent and intense heatwaves is more urgent than ever. Most cities and communities around the world are critically underprepared for the growing reality of heatwaves. This paper presents the system of systems that come together to generate heatwave risk and action in which can, in-turn, support community-level heatwave resilience: features of urban heatwave risk, heatwave vulnerabilities, and heatwave governance. We then present the heatwave version of the Climate Resilience Measurement for Communities: a systems-based approach for conceptualising and measuring disaster resilience. The framework was co-designed by researchers and practitioners and is based on the most widely applied community flood resilience measurement endeavor in the world. This is, to our knowledge, the only standardized and holistic, yet globally applicable, heatwave resilience measurement framework available.

1. Introduction

Heatwaves are a devastating natural hazard, and are increasing in frequency and intensity due to climate change (Meehl & Tebaldi, 2004; Russo et al., 2015). Recent record-breaking heatwaves have extended across large areas in highly populated regions of the world, for example in North America in 2021 and China, India, and Europe in 2022. The risks associated with heatwaves are also escalating due to intersecting socio-economic and demographic challenges such as rapid, unplanned, unregulated urbanisation; population growth; aging populations; and poverty (UNDRR 2022). While recent heatwaves have increased awareness of the immediacy and seriousness of the heatwave threat, significant questions remain about if and how better awareness will translate into effective resilience building actions that target the underlying drivers of heat risk. Many challenges remain in improving heatwave resilience including an absence of data and a lack of understanding about the direct and indirect linkages between heat impacts; both have been problematic for the governance of anticipatory planning and action to mitigate risks (QUT 2010; UNDRR 2022).

To improve resilience to future heatwaves, it is essential that stakeholders and at-risk communities develop a more holistic understanding of their heatwave risks and potential multi-sector, cross-scalar resilience strategies. However, while the concept of disaster resilience has become a key ambition of policy and programs within communities, governments, non-governmental organisations, and

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the private sector, what resilience means on the ground, and how it applies to specific contexts, is still not well understood (Bakkensen et al., 2017). Additionally, operationalising and measuring progress in building resilience is extremely challenging (Béné et al., 2015, 2017). Yet, measurement is critical for more accurate and nuanced tracking of key indicators to inform prioritisation, policy, and planning (Barrett, 2010) — measurement at the community scale, for example, is crucial for developing targeted interventions (Barrett, 2010) as well as providing accountability for local-scale program investments and local capacity-building.

This article presents a whole-of-system approach for conceptualising and measuring heatwave resilience that goes beyond the needs of a single sector such as healthcare, and beyond emergency planning into long-term planning. Because the CRMC approach is assessing heatwave resilience across multiple systems, by necessity it is broad rather than deep. It does not prescribe resilience-strengthening actions to be taken, rather it provides a snapshot of strengths and gaps across the whole heatwave resilience space, thereby identifying areas for further investigation and potential action. To our knowledge, the heatwave measurement framework presented here is the first comprehensive systems-based heatwave measurement designed to be used by practitioners across many different contexts.

The approach was developed through a co-design process involving researchers and practitioners to ensure that it is both theoretically robust and can support the practical application of resilience measurement leading to increases in heatwave resilience. Because it is designed to be used in multiple contexts with huge variety in data availability, data collection is flexible and adaptable to the local context. Further, the systems-based framework supports multi-stakeholder coalition building which is essential for equitable and cohesive heatwave governance.

This article first reviews the systemic, equity, and governance challenges faced by urban communities in the face of growing heatwave risks. It then presents our approach to disaster resilience, which has been developed and applied globally through the Zurich Flood Resilience Alliance (the Alliance). Next we describe the co-design framework development method and the heatwave resilience framework and tool, including key principles and design features. Finally, we describe the practical application process. A list of indicators and details regarding data used for measurement is provided in the Appendix.

2. Heatwaves: Key concepts and research

The IPCC (2021) defines a heatwave as, "[a] period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions." UNDRR, following WMO, states that, "A heatwave is a marked warming of the air, or the invasion of very warm air, over a large area; it usually lasts from a few days to a few weeks (WMO, 1992). Alternative definition: A heatwave is a marked unusual period of hot weather over a region persisting for at least two consecutive days during the hot period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds (WMO, 2020)" (UNISDR, 2015). In bringing together the disaster resilience and heatwave fields in the context of measuring heatwave resilience, also relevant here is the definition of a disaster. Following the Sendai Framework, a disaster is defined as "A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts" (UNISDR, 2015).

Bringing these two definitions together, for the purposes of the CRMC approach described here, a heatwave – or more fully a heatwave disaster for a community – is defined as, "a prolonged period of extreme heat, where temperatures are markedly higher than usual relative to typical local and seasonal conditions, that results in a serious disruption of the functioning of the community".

Heatwaves are expected to increase in all regions of the world under current rates of greenhouse gas emissions (Russo et al., 2014) leading to new regimes of temperature extremes outside observed historical precedents (Harrington et al., 2016). Recent studies using rapid attribution methodologies have found that record-breaking heatwaves are already occurring earlier in the season, are more likely, and are more extreme due to climate change. For example, the extreme heatwave experienced over large parts of the United Kingdom in July 2022 was found to be 40 times more likely because of climate change (Zachariah et al., 2022b). Likewise, 2022 heatwaves in India and Pakistan were found to be 30 times more likely (Zachariah et al., 2022a). It is predicted that by the middle of this century, heatwave conditions that are currently considered extreme and rare will become regular occurrences in many parts of the world.

Exposure and vulnerability are also growing as extreme heat events become more frequent and intense over some of the most populated and poorest urban centres in regions of Asia, the Middle East, and North Africa (ONU, 2018; Zittis et al., 2021). Climate change in these regions is already part of the complex interplay of factors that underpin food and livelihood insecurity which, in turn, is driving seasonal, temporary, and permanent migration to urban areas (ONU, 2018). The trend of rapid urbanisation is accelerating the scale of human exposure to the most severe impacts of heatwaves because of the combined impacts of the urban heat island (UHI) effect, high population densities, aging populations, and the growing rate of urban poor (ONU, 2018; Watts et al., 2015). Poverty and marginalisation drive millions of residents into unplanned and unregulated informal settlements in urban and *peri*-urban areas, many of which suffer from a lack of basic infrastructure and services for protection from extreme heat (and other hazards) (Satterthwaite et al., 2018; UNDRR, 2022; Keating et al., 2017). These residents are also more likely to work in the informal economy where they lack social and legal protections (Satterthwaite et al., 2018). Similarly in middle-income and developed nations, increasingly dense urban centres coupled with aging population structures is also increasing the risk of heat (Coates et al., 2014).

Climate change is increasing warm-season fatalities, and this trend is expected to continue (Vicedo-Cabrera et al., 2021; Zhao et al., 2021). There is a well-established link between extreme heat conditions and increased rates of morbidity and mortality (Green et al., 2019; Watts et al., 2015). Two of the most extreme and widely documented examples are the European heatwave of 2003 that resulted in an estimated 70,000 excess deaths (Robine et al., 2008) and the Russian heatwave in 2010 with an estimated death toll of 55,000

(Barriopedro et al., 2011). People that are particularly vulnerable to the effects of heat are the elderly, people with pre-existing cardiopulmonary and other chronic diseases, and very young children (Ebi et al., 2021). Heat can worsen cardiovascular illnesses, which are the primary cause of mortality during heatwaves (Ebi et al., 2021). Other illnesses that can be worsened by heat include kidney disease, respiratory disease, and diabetes, heat stroke, and severe dehydration (Ebi et al., 2021). Pre-existing mental and psychiatric illness can also be aggravated (Costello et al., 2009; Page & Howard, 2010). Heatwaves have a significant impact on mental health and well-being through direct heat exposure and heat-related sleep deprivation that causes stress, aggressive behaviour, and mental and physical exhaustion with resulting impacts on productivity and occupational risks (Berry et al., 2010; Ebi et al., 2021).

In addition to causing unnecessary levels of suffering and death, direct and indirect impacts of heatwaves on human, social, environmental, physical, and economic systems can have long term and cumulative consequences (Ebi et al., 2021; Lancet, 2022). Governments have been slow to act on heatwaves and most are critically underprepared for future extreme heat (Lancet, 2022). Data on heatwave impacts has been a major challenge and is usually not well collected or used in a timely and integrated way, leaving major gaps in policy-relevant data – especially in low- and middle-income countries (Green et al., 2019; UNDRR, 2022). The result is that the full consequences of heatwaves and underlying drivers of heatwave risks are often not well understood or planned for, limiting the scope for policies that target the root causes of socio-economic vulnerabilities and can help foster long-term systemic change (Green et al., 2019; Keith et al., 2021).

The next section of this article provides an overview of some of the intersecting heatwave challenges faced by urban populations and systems which inform our systems-based heatwave resilience measurement framework. Three overarching themes are used to examine heatwave risks and resilience: 1) risks to critical urban systems; 2) heatwave equity and vulnerability; and 3) the governance challenges and opportunities for developing holistic and anticipatory heatwave resilience planning.

2.1. Heatwave risks in urban areas

Urban residents and systems face an elevated exposure to heatwaves due to UHI effects. The UHI is now a well-documented phenomenon wherein the high density of heat retaining surfaces in urban areas raises ambient temperatures and prevents night-time cooling relative to rural areas (Bohnenstengel et al., 2011; Oke, 1973). In studies in cities in the United States, the UHI has been shown to raise daytime temperatures by around 0.5–4 °C (1–7 °F) and night-time temperatures by around 1–2.5 °C (2–5 °F) (Hibbard et al., 2017). Extreme heat that persists over several days and nights escalates risks to humans, animals, natural systems, and critical infrastructure. The intensity of the UHI is not constant but varies across urban spaces due to many factors including the size, volume, and density of buildings; population density; types of building materials; the presence of blue and green spaces; and climatic variables (Bohnenstengel et al., 2011; Kershaw, 2017; Sangiorgio et al., 2020). While many of these features of cities are difficult and costly to modify, understanding where and how heat builds up in urban environments as well as who or what is exposed allows for evidence-based resilience strategies, including better integration of heat risk considerations into urban planning.

Urban energy and transportation systems are complex lifeline systems that are particularly vulnerable to failures during heatwaves (McEvoy et al., 2012; Singh, 2021). These systems comprise multiple temperature-sensitive components which can fail under extreme heat resulting in, for instance, the buckling of railways, melting of bitumen roads, expansion of bridges in transportation systems; and reduced capacity for energy production, as well as multiple faults in energy transmission and distribution systems (Bollinger & Dijkema, 2016; McEvoy et al., 2012). Infrastructure failures experienced during recent extreme heatwaves have exemplified the limitations of physical infrastructure that is operating with little to no redundancy: is aging and/or not well maintained, and is not designed for current and future heat conditions under climate change (Forzieri et al., 2018; McEvoy et al., 2012). For example, in the January 2009 heatwave in south-eastern Australia, a combination of extreme heat, record energy demand driven by use of air-conditioning, and multiple equipment faults in electricity generation and supply systems forced the system into rolling blackouts during the peak of the heatwave when temperatures reached 45.1 °C (113.2 °F) (McEvoy et al., 2012). An estimated 500,000 people were impacted by the blackouts and the heatwave disruptions overall led to $800 million AUD ($528 million USD) in financial losses (Queensland University of Technology, 2010).

Healthcare systems come under extreme pressure during heatwaves due to the demand-side surge in heat-related illnesses as well as the supply-side pressures caused by medical facilities and staff conditions that are not adapted for extreme heat. Healthcare workers, medical facilities and medicine storage can be directly affected by extreme heat conditions or through power, transportation and communication failures that affect healthcare provision and access (Curtis et al., 2017). Many frontline health and community services providers are themselves under-resourced and vulnerable in heatwaves and may not be able to safely continue to operate, thereby exacerbating risks for the many vulnerable people that rely on them (Mallon & Hamilton, 2015).

While the direct impacts of heat may originate in isolated components of any urban system, it is the interconnectedness between multiple systems and potential for cumulative or cascading impacts that poses the greatest challenge to understanding and developing urban resilience (Bollinger & Dijkema, 2016; Curtis et al., 2017). Power failures during heatwaves are particularly damaging because they trigger disruptions to a wide range of other sectors and services, potentially exposing large populations to elevated risk or even life-threatening situations (Singh, 2021). Developing resilience requires not only changes to individual parts of systems, like making individual buildings or sectors more resilient, but actions that connect multiple systems and networks.

2.2. Heatwave vulnerability and equity

The impacts of extreme heat are unevenly borne across cities and communities, disproportionally affecting those with lower socio-economic and health status (Borunda 2021; Green et al., 2019; Kjellstrom, 2015; Lander et al., 2019; Mitchell & Chakraborty, 2018;

Renteria et al., 2022). In times of extreme heat, those people that are already living and working in the poorest or most marginalised conditions in cities often have both the greatest direct heat exposure and most limited adaptive options. People experiencing poverty and disadvantage are more likely to live in communities that have higher densities, with less green open spaces, weaker infrastructure, and greater urban degeneration (Bowen and Friel 2015; Singh et al 2019). They are also more likely to live in poor-quality housing that is badly ventilated and lacks air conditioning due to both equipment and running costs (Hatvani-Kovacs et al 2016).

Poverty is a driver of occupational heat stress with a greater likelihood of people working in low-paid physically demanding jobs in outdoor or hot indoor environments (Watts et al 2018; Lohrey et al 2021). Poorer people and those with insecure employment may also be more likely to prioritise income over health and lack either knowledge and/or agency in taking actions to protect their health in the workplace (Hoa et al., 2013; Lohrey et al., 2021). People in lower socioeconomic or marginalised groups are also more likely to lack access to safe transportation to get to and from work and school, as well as heat-resilient transportation needed to access cool spaces (Renteria et al., 2022) and medical facilities (Curtis et al., 2017). These and many other indirect impacts on individuals, families, and communities compound human suffering during heatwaves and have long-term implications because they reduce the ability to cope and recover from all shocks and stresses, which further exacerbates inequalities over time (Hallegatte, 2017; Lander et al., 2019).

Several studies from the United States have also shown that race is a critical factor in heat exposure and risk (Mitchell & Chakraborty, 2018; Renteria et al., 2022). In the United States, Black, Asian and Hispanic or Latino populations are significantly more likely to have multiple heat-related vulnerabilities compared to White populations because they are more likely to be experiencing poverty, live in inner urban areas, and rent their homes. The racial inequities in extreme heat exposure observed today in the United States have deep historical roots which have resulted from historic racially driven policy and planning practices (Borunda 2021; Wilson, 2020).

Compared to high-income countries, lower-and middle- income countries (LMICs) are more likely to lack the infrastructure, governance structures, and human and financial resources for heat adaptation. The risks of occupational heat stress are also greatest for those in low- and middle-income tropical countries (Kjellstrom et al., 2009). The impacts of extreme heat are generally predicted to be felt earlier and with greater impacts in lower latitude regions of the world where the most densely populated and poorer populations reside (Harrington et al., 2016). Global inequality is also found in heat-health related research, with the vast majority of studies being undertaken in high-income countries and very few studies in lower- and middle-income countries (Campbell et al., 2018; Green et al., 2019). As Green et al., (2019: 85) point out *"In some locations (such as some Australian cities like Brisbane or US cities like Phoenix) there have been more studies conducted than the entire continent of Africa, which strongly suggests that more evidence is needed to understand the localized and specific problems in low- and middle-income contexts"*.

To help build resilience to future extreme heatwaves it is now critical to prioritize multi-dimensional heat equity as a goal in the development of evidence-based strategies for anticipatory heat risk reduction and climate adaptation. This can only be achieved through more nuanced understanding of the underlying drivers of heat risks and vulnerabilities for specific localities. Resilience building needs to engage deeply with communities and ensure that planning encompasses the multiple dimensions of heat-equity and vulnerability including the structural factors that perpetuate inequities and inequalities and strategies to address them (Meerow et al., 2019).

2.3. Heatwave adaptation and governance capacity

Coates et al. (2014) estimated that between 1900 and 2011, heatwaves resulted in 4,555 deaths in Australia – more than from the total combined deaths from all other disasters. And yet, cities have been slower to act on heatwave resilience than other hazards. One hypothesis is that this is because to some extent heatwaves do not generate obvious physical or economic impacts in the same way as other hazards such as floods or cyclones. Heatwaves have been referred to as 'passive crises' because the impacts are more insidious and do not, in general, create the mayhem of other types of disasters (Queensland University of Technology, 2010; Ladds et al., 2017). Keith et al., (2021: 29-10) suggest that the lack of progress on heatwave governance relates to the 'invisibility' of heatwave as a hazard or disaster, stating that *"[h]eat is an outlier hazard – invisible, frequently chronic and subtly pervasive"*.

Context- and community-specific data on heatwave impacts is often either not collected or only emerges weeks or months after the heatwave has passed, leading to missed windows of opportunity for action. In addition to data on mortality and morbidity, data on issues such as missed school hours, rise in family violence and missed days of work are often not well collected or analysed in a systematic way (UNDRR, 2022). Context specific heat research and data is critical to inform the development of targeted heatwave strategies that understand the specific risks for vulnerable individuals and communities. For example, Hatvani-Kovacs et al., (2016: 609) in a survey of adaptive behaviours in Adelaide, Australia found that older generations who grew up at times with greater frugality were less likely to use air conditioning or move to cooler rooms in their homes; families with two or more children were less likely to check weather forecasts or plan for the day ahead; and those with tertiary qualifications utilised cooler areas at home and were more likely to stay longer at work to make use of air conditioning. They also found that pre-existing health conditions are potentially a stronger predictor of heat-related health problems than age yet those with pre-existing health conditions did not see themselves as more vulnerable, adapt their homes more, or plan to retrofit in the future.

Link et al. (2021) found specific heatwave livelihood resilience capacities and vulnerabilities amongst different household groups linked to migration biographies in Pune, India, and that these varied on small spatial scales. Lohrey et al., (2021:5) found that marked differences in the self-reporting of symptoms of heat-illness in different occupational groups of outdoor workers and slum dwellers in Hanoi, Vietnam could be explained by differences in age, sex, occupation, house ownership, night-time access to air-conditioning, income, use of weather forecasts and being a child carer. Such fine-grained but contextually critical knowledge of heat behaviours within social groups and within communities can be used to drive targeted messaging and strategies to enhance knowledge development about specific heat adaptation options and measures.

Another major governance-related barrier to building heatwave resilience is the fragmentation of planning authority; in many jurisdictions, there is no single organisation or department responsible for coordinating risk reduction and response for extreme heat (Abeling, 2015; Keith et al., 2021). Abeling (2015) found that in London, heatwave governance was integrated into public health planning and framed as a health response, which undermined a much-needed shift toward the consideration of heat risk in environmental, social, and technical sectors or spheres (Abeling, 2015:6).

Siloed responses dominate in planning and research, leaving major gaps in understanding and addressing the multidimensionality and complexity of heatwave impacts (Keith et al., 2021). The lack of whole system understandings and governance approaches creates major limitations to improving heat resilience, putting people and systems at greater risk (McEvoy et al., 2012). There is an urgent need for much greater cross-sector and cross-system governance on heat. The development of resilience metrics that cross scales and sectors is critical to developing a greater understanding of baseline conditions, identifying gaps, and assessing and communicating progress towards heat resilience in specific contexts (Keith et al., 2021).

3. Disaster resilience conceptual framework and resilience measurement approach

3.1. Disaster resilience conceptual framework

The concept of disaster resilience has become central within the discourses of disaster-related research, policy and practice, and established through the Sendai Framework for Disaster Risk Reduction (UNISDR 2015) which requires signatories to aim for '*preventing the creation of new risk, reducing existing risk and strengthening resilience of people and assets to withstand residual risk*' (UNISDR 2015: 10). Emerging initially in the ecological field to explain the amount of disturbance a system can absorb and retain its structure (Holling, 1973), the concept of resilience has been expanded to explore the response of systems or entities in response to stressors and shocks across a wide range of disciplines (Cutter et al., 2008). A primary objective of the focus on disaster resilience has been to better understand the conditions that facilitate socio-ecological systems to cope, re-organize, change, and learn in response to hazards (Cutter et al., 2008: 599). The key assumption is that a resilient system will have capacities and assets to employ absorptive, adaptive, and transformative strategies that will reduce its vulnerability when hazards strike (Béné et al., 2015; Cutter et al., 2008).

The Zurich Flood Resilience Alliance (henceforth 'the Alliance') is a multi-actor and multi-sector partnership formed by Zurich Insurance (Zurich Flood Resilience Alliance, 2023b). The Alliance has been delivering the Flood Resilience Measurement for Communities (FRMC) framework and tool since 2013 (Keating et al., 2017). To-date, between 2018–2024, the second version of the FRMC – called FRMC Next Gen[1] – has been applied in approximately 400 communities across 22 countries, generating unprecedented data and insights on the process of measuring and strengthening community disaster resilience. Early work within the Alliance involved conceptualising community flood resilience, and it was found that community flood resilience is far more than just 'bouncing back' with good relief and recovery or building robust infrastructure. Building from the experience of the FRMC, the Alliance developed the heatwave resilience approach described here and has been actively contributing to this field on a global scale since 2013. The Alliance comprises actors from NGOs, research, the private sector, and local communities working collaboratively with the goal of enhancing flood resilience through measurement, research, and advocacy (see section 3.2).

Following an extensive review of resilience definitions summarised in Keating et al (2016) the Alliance developed a shared definition of disaster resilience that underpins its conceptual and practical work, that is: *the ability of a system, community, or society to pursue its social, ecological, and economic development and growth objectives, while managing its disaster risk over time in a mutually reinforcing way*. This definition emphasises that the goal of disaster resilience is long-term well-being, including fundamental changes to systems where needed to prevent or adapt to the increase in disaster risk. It also seeks to reduce or eliminate the use of negative coping behaviors — negative strategies that individuals, households and communities take which undermine their long-term wellbeing, such as taking children out of school or the unsustainable use of natural resources — to address escalating natural hazards.

This definition and associated conceptual framework draw from several interrelated themes that are reflective of a broader shift in development and disaster thinking and practice over the last decade towards anticipatory risk reduction and resilience (Keating et al., 2017). These shifts have been driven by mounting evidence that dominant paradigms have not only failed to reduce disaster risk, but have contributed to both the creation of new risk and perpetuation of existing risk, risks that are disproportionally borne by those already experiencing poverty and other forms of vulnerability (Hallegatte, 2017). Further, a narrow and fragmented view of disasters, which focus on the symptoms – rather than underlying drivers of vulnerabilities – reinforce already unsustainable and inequitable systems and pathways. The following five themes reflect these changes and are fundamental to our approach:

1) a view that disasters are not 'natural' but emerge from a combination of natural forces and human actions made at all levels from the individual to the global;
2) the need to dramatically increase investments in pre-event risk reduction rather than only focus on emergency response and ex-post recovery;
3) that disaster resilience, climate change and sustainable development must be addressed in an integrated way;
4) that risks and vulnerabilities are contextual and place-based, influenced by local socio-ecological systems, governance, and political economies, and;

[1] For a description of the FRMC see Hochrainer-Stigler et al., 2021.

5) that there is a need to prioritise a holistic framing of development that is based on human well-being over a narrow and short-term economic growth focus. Overall, these themes significantly challenge core assumptions of dominant disaster management and economic-centric development paradigms.

While the view that disasters are naturally driven catastrophes persists, there is a deepening understanding that disasters involve the interaction of a hazard with exposure and vulnerability (Aitsi-Selmi et al., 2015) and are determined by dynamics operating at multiple spatial and temporal scales. This recognition expands the onus of responsibility for reducing disaster impacts and building resilience towards a broader range of actors and decision-makers from the micro- to macro- scale across the whole-of-society and presupposes the need for greater investment in ex-ante risk reduction. It also leads to the understanding that much greater attention must be paid to the historical and current structural and political processes underlying the creation and distribution of risks across a society. These processes have traditionally been neglected within disaster management and continue to be a critique of resilience planning (Meerow et al., 2019). Further, there is a greater recognition of the need for more equitable and holistic approaches to disaster resilience that include a much larger role for communities to set their own priorities, and are grounded in local knowledge, values and capacities (Cradock-Henry et al., 2018; Meerow et al., 2019).

3.2. Disaster resilience measurement

As resilience has increasingly become a focus of disaster policy and programming, the challenges of operationalising and measuring resilience have come to the fore, along with the development of many conceptual and practical tools and frameworks. Resilience metrics typically aggregate indicators of resilience proxies across a geographical location, issue, hazard, or a combination of these (Bakkensen et al., 2017; Cutter et al., 2008; Ostadtaghizadeh et al., 2015; Schipper & Langston, 2015; Asadzadeh et al., 2017; Sharif & Yamagata, 2016). Resilience measurement frameworks, models and tools are increasingly used to guide policy and initiative design, and to track the effectiveness of interventions (Barrett, 2010; Barrett & Headey, 2014; Cutter, 2016; Sharif & Yamagata., 2016). Cutter (2016) and Keating (2017) emphasis the important role that resilience measurement approaches can play in drawing attention to the more intangible or 'soft' system elements critical for disaster resilience.

However, it has become well recognised that measuring resilience is not without its challenges. Across the peer-reviewed and grey literature we find a proliferation of conceptualisations of resilience and measurement frameworks (Asadzadeh et al., 2017; Laurien et al., 2022). Because disaster resilience is a concept based in complex adaptive systems thinking, it is often conceptualised and measured using a multi-dimensional approach (Laurien et al., 2022); yet there are no agreed key variables or even dimensions that should be included in a measurement framework. Jones et al. (2021) and Schipper & Langston (2015) contend that the lack of conceptual agreement may be eroding confidence in the measurement endeavour altogether. In addition to the complexity created by conceptual ambiguity, applied measurement frameworks or tools must be practical and useful for practitioners (Béné et al., 2017). The authors' experience of co-designing the measurement approach (discussed in this paper) with practitioners was one of constant design tension to deliver a framework that is both short and straightforward enough to be practical and useable, but long and nuanced enough to be robust and comprehensive.

The FRMC was developed by a design team consisting of members from Zurich Insurance, two academic institutions, an international development NGO, and a humanitarian organisation. It was designed to measure a holistic set of pre-event community characteristics that were considered — on the best available evidence — to contribute to community-level resilience to flooding. The FRMC (and subsequently the CRMC) was specifically designed to be applicable in the majority of communities across the world. The indicators do not assume a base level of development or the existence of formal governance structures. The FRMC has predominantly been applied in developing country contexts, with significant variation in governance approaches and formality, and resourcing for disaster risk management and climate change adaptation. When a flood occurs in an FRMC community, impact measures are also taken. The theory here is that if enough measures were taken, then eventually individual indicators could be empirically linked (or not) to flood outcomes (Keating et al., 2017).

Following the focus on overall wellbeing and development as the overarching goal of disaster resilience in our definition, the sustainable livelihoods (SL) framework (DFID, 1999) was drawn upon to capture community assets and capacities. The five capitals of the sustainable livelihood's framework are the most prominent categorization of the indicators – called 'sources of resilience' – in the FRMC (DFID, 1999). This framing has been an inherent part of the measurement framework from inception, and strongly emphasizes the multidimensional nature of resilience (Keating et al., 2017). In addition to this, there are five other lenses that are used so that *"the suite of categorizations attached to each source provide for analytical depth by allowing for multiple perspectives on results"* (Keating et al., 2017). The FRMC framework is an index of 44 indicators – called 'sources of resilience' – that are assessed or graded against a four-point (A-D, A being high/desirable and D being low/undesirable) grading rubric. The FRMC framework and experience of applying it were the basis for the development of the heatwave version of the Climate Resilience Measurement for Communities (CRMC) approach, discussed below.

4. A systems-based heatwave resilience measurement framework

4.1. Framework development method

An extensive peer-review of the FRMC in 2020 found that several hazards other than floods would be well suited to an FRMC-like approach and that it would be feasible and indeed desirable to undertake multiple stand-alone hazards in parallel. The main motive for

expanding the FRMC approach into different hazards was the recognition that the approach was useful and useable and could be used for hazards other than floods, as well as the acknowledgement that communities are often exposed to multiple hazards and there is a need to facilitate co-benefits of resilience strategies and interventions. However, it was deemed critical to adhere to key principles and structure of the FRMC, including hazard specificity (resilience of whom, to what, for what), community centricity, the 5C/4R framework (explained below), and validation through measurements across multiple timeframes, including a post-event review. The multi-hazard tool that was developed is a revised, updated version of the FRMC — the Climate Resilient Measurement for Communities (CRMC), which can be used to measure community-level flood and/or heatwave. A wildfire version was developed and integrated into the tool in 2023; the CRMC has the potential to include further hazards over time.

The development of the CRMC used an iterative co-design process, see Fig. 1. The multi-tiered process involved a core writing team, a wider project team, and an expert panel who received and provided feedback. The expert panel comprised ten members, five of whom are primarily researchers and five primarily practitioners. The expert panel as well as the Alliance team and core writing team have extensive individual and collective experience which bridges both research and practice in resilience measurement and resilience building. The process involved two rounds of individual reviews, two review panel workshops (to accommodate different time zones) and a co-design workshop with the Resilient Cities Network, who are the first users of the CRMC in North America.

4.2. Underpinning concepts and framework structure

The CRMC approach to measuring heatwave resilience is systems-based and holistic in that it collects information from across multiple systems and then integrates information and facilitates the exploration of the interconnections. The Alliance uses a working definition of systems thinking to describe this approach, "*an integrated, holistic approach to looking at a situation or problem. Systems thinking recognizes that the world does not operate as isolated components or silos and seeks to understand the different elements work together to function the way they do.*" (Zurich Flood Resilience Alliance, 2023a). The process of using the CRMC requires collecting information from a wide range of data sources on topics ranging from, for example, the percentage of school children attending school; the extent of permeable surfaces; the robustness of the energy system; and the percentage of the community that has access to financial help.

The framework and tool guide users to think deeply about the whole community system and the interdependencies within it. They also help users to visualize connections between systems at different scales (e.g., how the community links up to municipal and regional scales and down to household and individual scales). Table 1 provides definitions for various conceptual frameworks that underpin the CRMC, which are also used as analytical lenses that enable users to identify connections to other aspects of resilience and the interdependencies which create those connections. Finally, it also helps users to think about how interventions and solutions can support more than just one element or source of resilience and helps to identify intended and unintended consequences.

Critically, the CRMC has been designed to be both practically usable in a majority of diverse contexts, as well as conceptually robust. The heatwave CRMC contains 50 sources of resilience, including both general resilience and heatwave resilience sources. It is acknowledged that this is a significant number of indicators for users to collect data against, grade and analyse. In the design phase, significant effort was invested into weighing up which constructs or concepts should be included in the CRMC. The CRMC is broad because it is capturing multiple systems. It is inevitable that some sources may not be relevant to all communities. Likewise, it is inevitable that some communities may be facing issues within their heatwave resilience that are not captured by the CRMC. These limitations are necessary in order to ensure that the CRMC is practical, near-universally applicable, and standardized.

The next sections outline the key findings and challenges from our experience of developing a heatwave resilience measurement

Fig. 1. Contributors to the CRMC, source: authors.

Table 1
Lenses of analysis for the Climate Resilient Measurement for Communities (CRMC).

CRMC framework lens	Definition (Zurich Flood Resilience Alliance, 2023a)
Five capitals (sustainable livelihoods framework)	
	The five livelihoods capitals; physical, financial, human, social, and natural capital. These five capitals are complementary; all five together help sustain and improve community inhabitants' wellbeing and provide a holistic picture of a community's resilience. The multiple capital approach has been popularized by the well-known and utilized Sustainable Livelihoods Framework (DFID). By exploring community resilience in this way, we are explicitly drawing out the links between community resilience and development more broadly.
Social capital	Social relationships and networks, including bonds that aid cooperative action and links that facilitating exchange of and access to ideas and resources.
Human capital	Knowledge, education, skills, health of the people in the community.
Financial capital	Level, variability, and diversity of income sources and access to other financial resources that contribute to wealth.
Natural capital	The natural resource base, including land productivity and actions to sustain it, as well as water and other resources that sustain livelihoods and wellbeing.
Physical capital	Things produced by economic activity from other capital, such as infrastructure, equipment, store inventory, crops, or livestock, etc.
Four properties of a resilient system	
	Four properties of a resilient system; robustness, redundancy, resourcefulness, and rapidity. Together, the 4Rs consider the quality of life, interactions, and interconnections at the community level, and therefore provide a "systems analysis" approach.
Redundancy	Functional diversity, for example having many evacuation routes.
Resourcefulness	Ability to mobilize when threatened, for example a community group who can quickly turn a community center into a cooling center.
Rapidity	The ability to contain losses and recover in a timely manner, for example access to quick finance for recovery.
Robustness	The ability to withstand a shock, for example bridges built to withstand flood waters or roads build to withstand extreme summer temperatures.
Themes	
	In the CRMC, each source is assigned one of 7 themes — assets, livelihoods, natural environment, life and health, critical systems, governance, and social norms. Questions in surveys are organized by these themes because they are typically initially easier for practitioners to work with than the other lenses.
Life and health	Sources of resilience that protect the life and health of community members.
Lifelines	Sources of resilience that relate to provision and continuity of critical infrastructure systems and essential supply chains and services.
Assets	Sources of resilience that are or protect physical assets in the community.
Natural environment	Sources of resilience that are or protect the health and sustainability of the natural environment, including in relation to disaster provisioning services.
Social norms	Sources of resilience that relate to culture and other informal norms in the community.
Governance	Sources of resilience that relate to development and disaster risk management governance arrangements.
Livelihoods	Sources of resilience that are or protect community livelihoods, both formal and informal, cash or otherwise.
Disaster Risk Management Cycle	
	The ongoing process by which governments, businesses, and civil society plan for and reduce the impact of disasters, react during and immediately following a disaster, and take steps to recover after a disaster has occurred. We define five stages of the DRM cycle: prospective risk reduction, preparedness, response, recovery, and corrective risk reduction. However, because it is a cycle, in practice the stages blend into one another.
Prospective risk reduction	Actions taken to avoid the build-up of new or increased risk, for example building regulations and land use planning that limit construction in the floodplain or building codes which require weatherproofing and light-colored roofs to reduce building heat in the summer.
Corrective risk reduction	The actions taken to reduce risk to already at-risk assets, such as building rain gardens to capture and slow surface flooding or weatherproofing homes so they remain cooler during heatwaves.
Preparedness	Precautionary actions taken prior to hazard events. At the household level, preparedness includes understanding your risk and knowing what actions you can take to avoid or reduce loss (such as moving papers and equipment off the ground when you receive a flood warning). At the community level, preparedness could include developing pre-established evacuation routes. At the district or national levels, preparedness could include humanitarian agencies prepositioning emergency relief supplies.
Response	Actions taken during and immediately after a disaster to contain or mitigate disaster impacts, including evacuation, search and rescue, first aid, and emergency relief distribution.
Recovery	The actions taken after a disaster (either in the short- or long-term) to help people cope with disaster impacts, reconstruct damaged physical systems (e.g., homes, roads, damaged flood protection structures) and restore services.
Context level	
	Each CRMC source is assigned to one of two contexts; community level or enabling environment. This distinction may assist in designing interventions, because it highlights at which level action or advocacy needs to be targeted.
Community level	Within the sphere of influence of the community, aspects that the community has direct control over, for example first aid knowledge.
Enabling environment	Outside the direct sphere of influence of the community; aspects that the community does not have direct control over. For example, 'integrated flood management planning' is done at a municipal scale, not a community scale, and is therefore part of the enabling environment for the community.

framework and explores learnings in adapting a measurement tool for community flood resilience to heatwave resilience. The co-design process and literature review confirmed that the urban environment is a valid focus for heatwave resilience measurement due to the combination of high population densities and the amplification of direct and indirect impacts with increasing UHI, as well as the complexity and interdependency of critical urban systems and their governance (Kershaw, 2017; Mehryar et al., 2022). While acknowledging that cities are situated in much larger networks and do not operate in isolation, individual city systems and the communities within them can have an enormous influence on local to global climate and sustainability transformations (Castán Broto et al., 2019).

In total fifty indicators – called 'sources of resilience' were developed across the five capitals for measuring heatwave resilience. Some sources of resilience are 'generic' in that they apply regardless of the hazard being measured, while others are specific to the hazard. While it is not feasible to explore all of these in detail here, the list of sources is provided in the Appendix and examples are

explored below to illustrate the way in which we have responded to key themes outlined in section 2, specifically our attempts to address the resilience of heatwave for critical urban systems, heatwave vulnerability and equity, and heatwave governance and capacity. Section 5 describes the process for applying the framework described here.

The measurement of the sources of resilience is done based on data that is collected in the community. Data is collected via household surveys, key informant interviews, focus group discussions, or via available secondary sources. That data is then compared to pre-defined grading rubrics that describes what each of the four (A, B, C, D) grades looks like for that source of resilience (Zurich Flood Resilience Alliance, 2023d). While each grading rubric is unique to each source, fundamentally the grades adhere to:

- A: Best practice for managing the risk
- B: Good industry standard, no immediate need for improvement
- C: Deficiencies, room for visible improvement
- D: Significantly below good standard, potential for imminent loss

4.3. Section 5 below provides a full description of the process of using the CRMC.Measuring heatwave resilience of critical urban systems

The heatwave CRMC was designed to measure the extent to which critical systems can withstand heatwave events and whether communities are currently anticipating future, more extreme heatwaves due to climate change. The sources of resilience that measure this core element of heatwave resilience are in the physical capital and natural capital groups (see Table 2).

Energy systems are critical drivers of risk and resilience in heatwaves that have direct impacts as well as indirect and cascading impacts on other systems when they fail. Therefore, the heatwave CRMC measures the redundancy, robustness and preparedness of the energy system and fuel supply to current and future heatwaves. Likewise, transportation and communication systems are key critical systems and the CRMC measures the extent to which these are likely to remain functional and accessible during heatwaves. Tree cover and natural capital are both mitigation measures for heat, and their presence or absence serves as a proxy for the likely intensity of UHI impacts. These are examples of a broader set of 18 physical and natural capital sources assessing the resilience of the build and natural environment.

The CRMC utilized a multi-dimensional approach to measure how heatwave resilience is being integrated across a system; from urban planning to the development of green infrastructure and actions taken at household scales. For example, in addition to measuring percentage of the landscape covered by vegetation canopy and the robustness of the vegetation canopy, the CRMC measures the density of the built environment; whether development and redevelopment policies or regulations ensuring permeability exist and are enforced; the extent to which there is a clear, transparent land use planning process; whether land use planning is informed by hazard risk maps and by climate change projections. These go beyond just the state of build systems and ecosystems to how those systems are established, maintained, governed, accesses, and though about in terms of their role in building community resilience. This is a step significantly further than seen in many assessment frameworks.

4.4. Measuring heatwave resilience equity

The CRMC also identifies a set of measurements that capture the different and intersecting ways in which people experiencing socio-economic disadvantage are more likely to experience higher heat exposure and less adaptive options (see Table 3). The extent to which a community's resilience is inclusive of all groups, including vulnerable and marginalised groups, has been embedded across the CRMC in four ways: 1) there are sources of resilience across all capitals that are explicitly designed to measure the equity of the community in regards to the distribution of, and access to, assets, capacities and opportunities; 2) there are sources of resilience that measure the extent to which the governance system is inclusive and representative of all groups; 3) the percentage bands for grading sources are designed to capture all groups e.g., to be graded the highest score band of 'A' the source must apply to over 95 % of the community, and 4) the data of relevant sources can be disaggregated for social, age, disability and marginalisation. These sources are concentrated in but not limited to social, human and financial capital.

Healthcare accessibility measures how adapted the healthcare system is to the social, cultural, and physical needs of the community

Table 2
Sources of resilience that measure heatwave resilience of critical urban systems.

Capital group	General resilience or heatwave resilience	Source of resilience (indicator) name
Physical	General resilience	Energy supply continuity
		Transportation system continuity
		Communications system continuity
	Heatwave resilience	(Heatwave) Emergency infrastructure and supplies
		Continuity of healthcare system during disaster (heatwave)
		Availability of clean, safe water (during heatwaves)
Natural	General resilience	Tree cover
		Permeable surfaces
		Land/water interface health
	Heatwave resilience	Use of natural capital for heat management
Financial	Heatwave resilience	(Heatwave) Risk reduction investments

Table 3
Sources of resilience that measure heatwave resilience equity.

Capital group	General resilience or heatwave resilience	Source of resilience (indicator) name
Human	General resilience	Secondary school attendance
		Food availability
		First aid knowledge
	Heatwave resilience	Heatwave vulnerability awareness
		Heatwave protection knowledge
		Worker protection for heatwaves
Social	General resilience	Healthcare accessibility
		Mutual support
		Community safety
		Family violence and response planning
		Intra-community equity
		Inter-community equity
Physical	Heatwave resilience	Continuity of education during disaster (heatwave)
		Household heat adaptation
Financial	General resilience	Household access to discretionary funds
		Community financial health
	Heatwave resilience	Business continuity (during heatwave)
		Household income continuity (during heatwave)
		Energy affordability

in normal times. A resilient healthcare system can adapt to ensure that all social groups, including all vulnerable groups are able to take the steps required to obtain healthcare and can access healthcare to meet their needs. The CRMC measures the availability of healthcare that is in safe physical reach of the community; and that meets the needs of all groups in the community, especially vulnerable and marginalized groups. The CRMC also assesses equity in the community and whether people in the community feel that resources are distributed equitably or whether there are significant equity gaps. To do this it measures a range of perceptions, including whether people perceive that people get paid fairly; those children have equal educational opportunities; and that people are treated fairly when applying for jobs in the community. It also includes a range of indicators that measure whether people in the community feel that they are advantaged or disadvantaged compared to other neighboring communities.

The CRMC has a range of measures for assessing both the community's access to financial assets in normal times and in heatwaves. The approach measures how many households are below the national poverty line and how many households are below the median national income. It also measures households' access to discretionary funds by calculating the percentage of households that can absorb a loss of income or sudden expense of up to one week worth of expenses. Heatwave specific measures in the CRMC measure business continuity planning for heatwaves and for households. The tool also assesses whether there is a government budget or other financing for heatwaves, which could include pre-event preparedness, heatwave risk reduction activities and/or heatwave response.

Several sources assess safety and security – a key element of both general and heatwave specific resilience. While acknowledged by the expert review panel as a sensitive topic to discuss at the community scale, safety and security was considered important as there is evidence that heatwaves are linked to an increase in family violence (Lander et al., 2019; Sanz-Barbero et al., 2018). Awareness by disaster response personnel about the causes of family violence during and following disasters in general, and within specific contexts, is a crucial factor in addressing this problem (Bradley et al., 2021). For example, Sanz-Barbero et al., (2018) found that there was a several days delay between the onset of extreme heat and the increase in family violence in Madrid; and that this time lag would allow preventative measures to be put in place. Accordingly, we have included sources such as underlying community safety, measured by assessing people's level of concern about becoming a victim of crime in their local area. Another source measures the extent to which family violence prevention is incorporated into heatwave response plans and whether disaster response personnel have been trained in family violence protection.

Household heat adaptation is a source of resilience that has been included in the CRMC to measure the percentage of households taking some type of action to address heat risk. This can include, for example keeping the house cool (e.g., putting up window blinds, insulating, planting trees or other vegetation); creating a cool roof (e.g., painting the roof); having active cooling (e.g., fans, air conditioning). The CRMC also measures the perception of knowledge and action of community members on heat, for example the percentage of households that are taking some type of protective measure to address heat risk; how well people perceive their awareness about how to protect themselves and others during a heatwave; and people's perception of their understanding of heatwave vulnerabilities.

Worker protection for heatwaves is a source of resilience that has been included in the CRMC to measure the percentage of community members that would feel protected while at work during a heatwave. People continue to work during heatwaves when there are no worker protection laws, policies, or plans for heat or existing laws/policies/plans are not enforced. People may not be aware that worker protections exist, or they may not have any ability to change their work situation. People also keep working because they cannot afford to lose income or for other reasons (e.g., they are providing an essential service). Steps can be taken in the workplace to eliminate or minimize the risks associated with working during heatwaves. This may include cancelling certain work tasks, rescheduling tasks to cooler parts of the day or waiting for hot conditions to pass, paid leave, additional breaks, or upgrading facilities with cooling devices.

4.5. Measuring heatwave resilience of governance systems

In urban contexts, improving the enabling environment (e.g., service delivery, governance, infrastructure, policies, access to social protection) can have beneficial synergistic effects on the capacities of households, communities, and higher-level systems (Béné et al., 2015: 10). Throughout the co-design process, the role of stakeholder engagement and coalition building to improve the systemic capacity to address risk and build resilience was a strong theme. The ways in which the community and its key stakeholders can engage to improve heatwave resilience that were identified in the co-design process and are outlined in Table 4.

The role of the health sector as a key stakeholder group with knowledge about baseline health conditions, the social context, and community resilience strategies is critical. The intention is that use of the CRMC will provide a platform for stakeholders to develop deeper relationships in support of increased collaboration and improved heatwave governance, which is fundamental for transformational and systemic change.

Our peer-review process identified that a post-heatwave recovery period does not exist in the same way as other disasters such as floods, because there is less obvious and catastrophic damage to homes and infrastructure. Therefore, the recovery phase for heatwaves must emphasize learning and improving systems and greater investment in risk reduction. Some of the key new sources added to the CRMC as it was adapted from the FRMC include a measure of whether there is a system in place for the collection and use of data about indirect impacts of heatwaves to inform future strategic planning for resilience; whether the data is widely used by key stakeholders and agencies to improve heatwave management; and whether climate change projections and climate service data are widely used in decision-making.

Measuring the extent to which climate change information is used in urban planning is still lacking in many resilience measurements tools (Mehryar et al., 2022). An important development within the CRMC tool has been the development and integration of resilience measures on climate change adaptation and awareness. Across the CRMC there are now multiple measures that track how well embedded the use of climate change data is in community and disaster planning. One of these measures — 'climate change adaptation planning and investment' —is designed to identify whether governments understand projected climate changes; have developed and have budgets for climate change adaptation; and whether government has reviewed capital investment to assure that climate change has been satisfactorily addressed.

We have also added a novel measure – the impact of climate change on disaster response personnel. The source recognizes the increasing burden on disaster response workers and that people on the frontline are facing more frequent and compounding disasters. It measures whether the present needs of disaster response personnel are being met through the provision of training, resources, and support; as well as whether disaster risk managers are actively planning for increasing needs in the future.

Climate change awareness in the community is primarily captured through three sources: Awareness of how nature mitigates (heatwave) risk; Climate change and risk awareness, and; Climate change action. Together, these three sources of resilience represent the perceptions of community members that climate change poses a present and increasing risk to the community; that they support action to address this risk and that the understand the role of natural environments in helping reducing risk and delivering multiple benefits.

5. Applying the CRMC heatwave resilience measurement

Upon application, the CRMC is available for use in not-for-profit contexts, where the use of the CRMC is part of a project or initiative

Table 4
Sources of resilience that measure heatwave resilience of governance systems.

Capital group	General resilience or heatwave resilience	Source of resilience (indicator) name
Human	General resilience	Climate change action
	Heatwave resilience	Climate change and (heatwave) risk awareness
		Awareness of how nature mitigates (heatwave) risk
Social	General resilience	Social inclusiveness of disaster risk management
		Local leadership
		Disaster response personnel
		Trust in local authorities
	Heatwave resilience	(Heatwave) Risk reduction planning
		(Heatwave) Response planning
		Stakeholder engagement in (heatwave) risk management
		(Heatwave) Risk mapping
		Disaster (heatwave) impact data collection and use
Physical	Heatwave resilience	(Heatwave) Early warning
		Heatwave forecasting and dissemination networks
Natural	General resilience	Land use planning
		Resource management
Financial	General resilience	Local government financial capacity
		Public infrastructure maintenance budget
		Climate change adaptation planning and investment
	Heatwave resilience	Heatwave action-plan budget
		(Heatwave) Risk reduction investments

that will have direct benefit to the community. Typical users include NGOs and humanitarian organisations, municipal governments and other community development or disaster resilience-oriented programs. The CRMC is designed to sit within a wider program of community development or disaster resilience strengthening. The CRMC is understood as one input into a broader community engagement, intervention selection and design process.

The steps involved in applying the CRMC process and software are set out in Zurich Flood Resilience Alliance (2023c) and summarised here. The first stage of the CRMC process is to set up the project, select the community/ies where the CRMC will be applied and develop a solid understanding of the community's characteristics. This includes defining the boundaries of the community, understanding the population groups – in particular vulnerable or marginalized groups, identifying and building relationships with key stakeholders.

Each source of resilience has attached to it data collection questions, that form the evidence for the grading. Data are collected via household surveys, focus group discussions, key informant interviews, and via already available secondary source information. Once practitioners have a solid understanding of the community and have developed relationships with key groups and stakeholders who are relevant to community disaster resilience, they set the study up using the CRMC software. This involves selecting which data collection methods will be used to collect data for each source of resilience. In this way, users customize the data collection to the community's context. At this stage fieldworkers, who collect the data, are often recruited. The CRMC software allows the user to assign surveys to fieldworkers, ready for collection. Users can also add their own additional questions to the surveys, if they wish to use the exercise to collect other data relevant to their work with the community.

Fieldworkers collect the data on their smart device using the CRMC app, by conducting household surveys, focus group discussions and key informant interviews. Data can be collected offline and uploaded at a later time, if internet connectivity is unreliable. Secondary source information is entered directly into the web platform. Once data collection is complete and uploaded into the system, the user team begins the grading stage. During grading, the CRMC software takes users through each source of resilience – it displays the definition of the source, the grading rubric and the data collected against that source. Users compare their data to the grading rubric and assign the source a grade from A-D.

Once all sources of resilience are graded, users utilise the CRMC software data cockpit to visualize and explore their results. They can also download their grades as well as raw data (for example household survey answers) for further analysis. The results can be explored along the various lenses outlined in Table 1, which adds much analytical depth. The results of the CRMC highlight both strengths and gaps in the community's heatwave resilience. Strengths can be leveraged to address gaps. It is critical to note that the CRMC does not tell users what interventions to implement or even which gaps to prioritise. Not all gaps highlighted by the CRMC will be relevant to the community in question or actionable in the user's program of work. Some identified gaps will be issues that can be tackled by the community themselves or a group of local stakeholders, others might be the subject of advocacy to local authorities for them to take action around.

CRMC results should not be compared across communities, as each community is unique and comparisons run the risk of painting some communities as "better" than others. Instead, the CRMC results are designed to be compared in the same community across time. By applying the CRMC every 2–3 years enables tracking of community heatwave resilience over time. After the first CRMC application in a community, subsequent applications include an additional assessment stage where users compare previous grades to new grades to explore what actions – by them or other stakeholders – might have led to grade changes over time.

6. Conclusion

Understanding what makes a community resilient to heatwaves is context specific, necessitating building better knowledge and learning systems at the local level that are also integrated with different governance levels and knowledge communities (i.e., sectoral, 'expert' and local knowledge). This paper has reviewed the system of systems that come together to generate heatwave risk and action in which can, in-turn, support community-level heatwave resilience: features of urban heatwave risk, heatwave vulnerabilities, and heatwave governance. We then presented our framework for measuring community heatwave resilience across these three elements, using the holistic five capitals approach. While the breadth of concepts presented here are not new, the development of an integrated framework and tool that aims to measure whole-of-system heatwave resilience at the community scale and can be used across many contexts by practitioners over multiple timeframes, and with a post-event validation is, to our knowledge, a novel approach.

It is hoped that the development of a systems-based framework for heatwave resilience will help practitioners develop strengthened ex-ante heatwave planning that is community specific, and which can help enable identify the many causal factors and underlying drivers of socio-economic vulnerabilities related to heatwaves. The broader goal is to support planning approaches that take a holistic approach to disaster resilience which are needed to target the root causes of risk and vulnerability to support deeper and more transformational systems change. While undertaking the process of heatwave resilience measurement does not in any way guarantee that resilience will improve, it has a key role to play in supporting improved capacity building and guiding the process of improved heatwave governance. The CRMC for heatwave is available for use at no cost in not-for-profit contexts that provide tangible benefits to communities (Zurich Flood Resilience Alliance 2023d).

CRediT authorship contribution statement

Rubenstein Naomi: Project administration, Writing – original draft, Methodology, Conceptualization. **Keating Adriana:** Writing – original draft, Supervision, Methodology, Conceptualization. **MacClune Karen:** Writing – original draft, Conceptualization. **Norton Rachel:** Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Naomi Rubenstein reports financial support was provided by Zurich Insurance Company Ltd. Adriana Keating reports financial support was provided by Zurich Insurance Company Ltd. Karen MacClune reports financial support was provided by Zurich Insurance Company Ltd. Rachel Norton reports financial support was provided by Zurich Insurance Company Ltd. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper].

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Appendix

The table below sets out the sources of resilience (indicators) in the CRMC heatwave framework and details on the elements in each grading rubric. The source definitions are abridged and we have not included full details on the grading rubrics or data collection details because, in addition to making the journal article unmanageably long, the detail provided here is not intended to enable use of the CRMC. Parties interested in using the CRMC (at no cost, in a not-for-profit context) or researchers interested in the content of the framework should reach out to the Zurich Flood Resilience Alliance.

Source of resilience name	Definition (abridged)	Grading rubric element(s)
Financial capital		
General resilience sources		
Household access to discretionary funds	This source measures whether people in the community have the financial resources and flexibility to address sudden financial demands.	% of households are able to absorb a sudden expense or loss of income of up to one week of typical expenses.
Community financial health	This source assesses how many households in the community are below the national poverty line, and how many are below the median national (or locally representative) income.	Share of households above the national poverty lineANDShare of households that have an income/wealth above the national median.
Local government financial capacity	This source measures how much scope and flexibility the local government has to raise funds, and how transparently and effectively they manage those funds.	Sources of independent revenue for local governmentsANDTransparency and accountability of local public finances
Public infrastructure maintenance budget	This source measures whether the government has a dedicated budget for maintenance of public infrastructure, whether it is sufficient to address priority needs, and whether it is spent equitably.	Existence of a dedicated annual budget for maintenance of public infrastructureANDSufficiency of the budget to address maintenance needs/there is no critical maintenance backlogANDMaintenance equitability across the jurisdiction
Climate change adaptation planning and investment	This source measures whether climate change and the need for climate change adaptation is explicitly considered in government investments and planning.	Climate change modellingANDClimate change adaptation plansANDClimate change adaptation budgetsANDClimate change reviews of planned capital investment
Heatwave resilience		
Business continuity	This source measures whether businesses operating in the community or employing a number of community members have operational and financial continuity plans in place to minimize impacts in a heatwave.	% of the businesses operating in the community or employing community members have a plan for continuity of operations in the event of a heatwave.
Household income continuity	This source measures whether households in the community can maintain their income/livelihoods in the event of a heatwave.	% households that would be able to maintain their income during a heatwaveAND% households that would need to make decisions about income vs. heat exposure to maintain their income
Risk reduction investments	This source measures whether there is a budget for disaster risk reduction, and whether funds are used to pro-actively address community heatwave risk.	Budget or funding mechanism for heatwave risk reduction activitiesANDEquitability of heatwave risk reduction investments
Energy affordability	This source assesses the community's financial vulnerability to heatwaves by assessing current household/business energy burden.	Share of homes and businesses in the community are energy burdened

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(*continued*)

Source of resilience name	Definition (abridged)	Grading rubric element(s)
Heatwave action-plan budget	This source measures whether there is a government budget or another type of financing for heatwaves.	Availability of government budget or other financing mechanismAndaccessibility and rapidity of fundingAndaccessibility and rapidity of funding
Human capital		
General resilience		
Secondary school attendance	This source measures the level of educational attendance in the community in normal times and whether attendance is equitable across genders.	% of secondary school age girls that regularly attend schoolAND% of secondary school age boys that regularly attend school
Food availability	This source assesses whether people in the community regularly have enough food to eat in normal times.	% of households in the community someone went to bed hungry in the last 4 weeks because there was not enough food to eat
First aid knowledge	This source assesses the first aid knowledge in the community.	% of adults in the community have received first aid training in the last 5 years.
Awareness of need for climate change action	This source assesses the community's attitude to climate change action, specifically whether people in the community believe that more action should be taken in the community to address climate change.	% of people in the community agree or strongly agree that the community should be taking greater action to reduce the risks of climate change
Heatwave resilience		
Awareness of climate change risk	Assess the community's awareness that heatwaves are a present hazard that is being impacted by climate change and will continue to worsen in frequency and intensity.	% of people in the community agree or strongly agree that climate change is making heatwaves more frequent and severe
Awareness of how nature mitigates risk	Assess the percentage of the community that can name at least one environmental management action that can both protect nature and also reduce heatwave risk.	% of people in the community agree or strongly agree that a healthy natural environment reduces heatwave risk
Heatwave vulnerability awareness	This source measures whether people in the community are aware of the dangers of extreme heat exposure, and the social and physiological factors that increase vulnerability to heat.	% of people in the community agree or strongly agree that they know which characteristics and activities make people more vulnerable to heatwaves
Heatwave protection knowledge	This source measures whether people in the community know how to protect themselves and others in a heatwave.	% of people in the community agree or strongly agree that they would know how to stay cool and prevent themselves and others from suffering heat-related illness during a heatwave.
Worker protection for heatwaves	This source measures the percentage of workers in the community that would feel protected while at work during a heatwave.	Share of workers in the community that feel protected while at work during a heatwave.
Natural capital		
General resilience		
Tree cover	A variety of native or locally adapted and beneficial tree and shrub species provide shading to the landscape. Trees provide shade and cool the air through evapotranspiration. They also hold soils in place and encourage water retention during rains.	% of the landscape that is vegetatedANDBiodiversity and ecosystem robustness
Permeable surfaces	The proportion of the landscape surface that is effectively permeable (soils, green space, water surfaces, shrub and tree cover, dirt or paver roads, permeable pavement, green roofs).	Land surface permeability in and around the community
Land use planning	This source assesses whether there is a clear, transparent and risk-informed land use planning process.	Presence of a clear, transparent land use planning processANDUse of hazard and risk mapsANDUse of climate change projections
Resource Management	This source explores the management of natural resources and whether the natural resources that are most important to the community are managed in ways that benefit the community.	Community engagement, local and expert knowledge, and direct benefits in natural resource managementANDCondition and sustainability of natural resources
Land/water interface health	The boundaries between land and freshwater bodies (marshes, streams, rivers, ponds, lakes) are managed to protect natural waterways and preserve wetlands. The boundary between land and ocean (where relevant) is protected by engineered structures, dunes, wetlands, mangroves, and/or reefs.	Protection of river and stream banksANDProtection of natural wetlands and marshesANDProtection of coastal communitiesANDConsideration of climate change and sea level rise in management
Heatwave resilience		
Use of natural capital for heat risk management	This source assesses the degree to which the role of natural capital in heat reduction is recognized, and the degree to which natural capital is being actively used for heat risk reduction in communities.	Government recognition that natural capital can be used to reduce heat, particularly in heavily built up areasANDPolicies, plans and regulations resulting in natural capital being preserved or restored to reduce heat
Physical capital		
General resilience		

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Source of resilience name	Definition (abridged)	Grading rubric element(s)
Energy supply continuity	This source assesses the redundancy, robustness, and preparedness of the energy system and fuel supply to current and future shocks and stresses.	Protection of fuel supply from interruption during and after extreme eventsANDContinuity of energy generation systems during extreme events and times of demand surgeANDEnergy systems preparation to handle events more extreme than have been seen in the past
Transportation system continuity	This source measures the performance of community transportation systems that support daily life and emergency response.	Accessibility of community during and after extreme eventsAND Safety and reliability of public transit systems in all weather conditions
Communications system continuity	This source is assesses the continuity of communications systems such as landline telephones, cell phones, television, radio, radio two-way communication, internet, etc.	Communications systems available to community membersANDReliability of communications systems, including during and after extreme events
Heatwave resilience		
Early warning	This source assesses whether community members can access heatwave early warnings, and whether those warnings are understandable and actionable.	% of community members receive heatwave early warningsANDEase of understanding and actionability of warnings
Continuity of education during disaster	This source assesses the rapidity and robustness of schooling in the event of a heatwave.	Impact of heatwave on education deliveryANDAccessibility of school buildings during a heatwaveOR Duration of interruption to education during heatwaves
Emergency infrastructure and supplies	This source looks at the physical elements that help community members prepare and respond in the event of heatwaves.	Availability of appropriate infrastructure and equipment to protect lives and livelihoods during heatwavesANDTesting and maintenance of heatwave emergency infrastructure and equipmentANDEquitability of access to the infrastructure and equipment
Continuity of healthcare during disaster	This source assesses the ability of healthcare facilities to continue to function during a heatwave.	Preparedness of healthcare facilities to potential heatwave impacts on healthcare facilitiesANDAccessibility of healthcare facilities, including for all vulnerable and marginalized groups
Heatwave forecasting	This source assesses whether short term (days) heatwave forecasting capabilities exist, whether forecasts are delivered to authorities for dissemination, and whether forecasts are delivered in a timely fashion and in straightforward language such that authorities know what the forecasts mean and know how to use them.	Existence of heatwave forecasts/warnings or daily weather forecastsAND Communication of heatwave forecasts/warnings to authorities in ways they can understand and use
Household heatwave adaptation	This source is about what actions households are taking to protect themselves from heatwaves.	% of households have taken at least some type of protective measure to address heat risk.
Availability of clean, safe water	This source assesses whether everyone in the community has access to sufficient safe and clean water.	Disruption of clean drinking water supply during heatwavesANDContinuity strategies and backups for possible heatwave impacts on water supplyANDAccessibility of clean water supply including during heatwaves
Social capital		
General resilience		
Mutual support	This source looks at the extent to which people in the community feel that they give and receive support when needed.	% of people feel like they can rely on others within the community to help them in a time of need.
Social inclusiveness of disaster risk management	This source measures how socially inclusive the community is in disaster risk management.	What social groups, including all vulnerable and marginalized groups, have active input into decisions about disaster risk management.
Community safety	This source measures peoples' feelings of safety in the community in normal times through how worried they are about becoming a victim of crime in their local area.	More than 95 % of community members disagree or strongly disagree that they are worried about becoming a victim of crime in their local area.
Local leadership	This source is about evaluating the extent to which people in community feel that local leadership acts in the best interest of the whole community rather than just some groups.	% of people agree or strongly agree that local leaders act in the best interests of the whole community rather than only some groups.
Disaster response personnel	This source measures whether there are provisions to support disaster response personnel in responding to and supporting the recovery from disasters.	To what extent the present needs of disaster response personnel in the community are being metANDPlanning for how emergency response personnel needs might change in the future due to climate change
Healthcare accessibility	This source measures how well adapted the healthcare system is to the social, cultural and physical needs of the community in normal times.	Availability of healthcare in the community and whether it is in safe physical reach for the whole communityANDTo what extent the healthcare system meets the needs of all groups, especially vulnerable or marginalized groups.
Trust in local authorities	This source measures the level of trust that community members have in local authorities, specifically the police, local government, and emergency services.	% of people agree or strongly agree that the police in this community are trustworthyAND% people agree or strongly agree that the local government in this community is trustworthyAND% of people agree or strongly agree that the emergency services in this community are trustworthy

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Source of resilience name	Definition (abridged)	Grading rubric element(s)
Intra-community equity	This source looks at equity in the community and whether people in the community feel that resources are distributed equitably or whether there are significant equity gaps.	% of people agree or strongly agree that people that work in this community get paid fairlyAND% of people agree or strongly agree that all children in this community have the same educational opportunitiesAND% of people agree or strongly agree that all people get treated fairly when applying for jobs in this community
Inter-community equity	This source looks at equity between this community and surrounding communities.	% of people agree or strongly agree that this community is financially supported by government to the same extent as other neighboring communitiesAND% of people agree or strongly agree that children across this community have equal educational opportunities with children in other neighboring communitiesAND % of people agree or strongly agree that people across this community have equal employment opportunities with people in other neighboring communities
Heatwave resilience		
Risk reduction planning	This source assesses whether there is a heatwave risk reduction plan for this community, whether the plan includes both prospective and corrective risk reduction actions, and whether the plan is regularly reviewed and updated.	Presence of a heatwave risk reduction planANDWhether the plan includes both prospective and corrective risk reductionANDWhether plans are regularly reviewed and updated
Response planning	This source measures whether there is a heatwave response plan for this community that includes targeted plans to meet the specific needs of all social groups, including all vulnerable and marginalized groups.	Presence of a heatwave response plan for this communityANDWhether the heatwave response plan identifies all social groups, including all vulnerable and marginalized groups, and has targeted plans to meet their specific needsANDWhether the heatwave response plan is regularly tested and updated with all participating organizations.
Family violence and response planning	This source measures whether family violence prevention is incorporated into heatwave response plans. It also measures the extent to which emergency response staff have received training in family violence prevention.	Inclusion of family violence prevention in heatwave response plansANDShare of disaster response personnel who have been trained in family violence protection
Stakeholder engagement in risk management	This source looks at level of stakeholder engagement and collaboration in heatwave risk management planning and action.	Share of key stakeholders that should be actively engaged and collaborating on heatwave risk management planning and action are engaged and active.
Risk mapping	This source measures whether heatwave risk mapping has been undertaken and whether the results are being used in heatwave risk management planning and action.	Whether heatwave risk mapping has been done for this community in the last five yearsANDWhether heatwave risk mapping includes a vulnerability componentANDWhether heatwave risk maps are used in risk management planning and action
Disaster impact data collection and use	This source measures whether there is a system in place for the collection and use of data about the direct and indirect impacts of heatwaves to inform future strategic planning for resilience. The source also considers whether future climate projections or climate service data are being used for decision-making.	Presence of is a system for collecting data on direct and indirect heatwave impactsANDUse of this data is by key stakeholders and agencies to improve heatwave managementANDUse of future climate projections and climate service data in decision-making

Data availability

No data was used for the research described in the article.

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