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Developing a Heat Vulnerability Indicator in Australia Incorporating Health Outcome and Built Environment Data

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ABSTRACT

Extreme heat poses a major threat to population health. Heatwave frequency, magnitude and duration are expected to increase through climate change, requiring resilient planning to mitigate the effects of heat on vulnerable populations and to prepare the health system for the impact of intense heat exposure in the future.

Existing heat vulnerability indicators do not include linked health data at a fine spatial level and do not consider urban morphology properties that are now known to be important in the assessment of population vulnerability to extreme heat. This study aims to produce a fine-level Heat Health Vulnerability Indicator (HHVI) that integrates linked population health data, demographic determinants, environment, and urban morphology parameters into weighted spatial layers of exposure, sensitivity and adaptive capacity.

The resulting spatial indicator identifies areas that are vulnerable to extreme heat, along with the associated human health outcomes and the potential mitigating or amplifying effect of the built environment. A case study for the state of New South Wales, Australia, highlights the indicator's suitability to inform future planning decisions that lead to improved health and habitat interventions for climate-resilient cities.

Keywords: heat vulnerability, urban morphology, linked health data, environmental health.

Introduction

Heatwaves are causing more excess deaths than any other natural hazard in Australia (Nairn and Fawcett, 2014; Jian et al., 2015; NSW Health, 2022). The predicted increased frequency and severity of extreme heat through climate change (Haines and Ebi, 2019), along with a growing population expected to reach up to 49.2 million people by the year 2066 (Australian Bureau of Statistics, 2018), will, over the coming decades, lead to increased pressure on Australia's health infrastructure (Toloo et al., 2014; Wondmagegn et al., 2021). While climate change and population growth are seen as key drivers of risk, associated rapid urban growth, densification, and increasing demand for new housing stock in Australian towns and cities, further underpins the need for climate-sensitive urban planning and design to mitigate the adverse effects of extreme heat on population health.

The aim of this study is to generate a new and improved understanding of population vulnerability to extreme heat by producing a fine-grained HHVI, which integrates linked

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population health data, demographic determinants, environment and urban morphology parameters into weighted spatial layers of exposure, sensitivity and adaptive capacity. Representing areas that are vulnerable to heat by relating human health, built and natural environment factors, the indicator can reveal salient features that contribute to larger spatial patterns.

This paper presents a detailed methodology to create the HHVI, describing the advantages and challenges of utilising linked population health data (e.g., data access, ethics and confidentiality issues). The indicator's utility will be demonstrated via a case study located in the Australian state of New South Wales, highlighting its suitability. The HHVI is expected to provide valuable insight for researchers, policy, and decision-makers to help inform future planning decisions, adapt to the impact of extreme heat, and improve health and habitat conditions for climate-resilient cities.

Literature Review

Despite the impact of extreme heat on human health being widely recognised and studied (Barnett *et al.*, 2013; Coates *et al.*, 2014; Nairn and Fawcett, 2014; Jian *et al.*, 2015; CRC for Water Sensitive Cities, 2016; Hughes *et al.*, 2016; Bodilis *et al.*, 2018; Pfautsch and Rouillard, 2019; State Government of NSW and Department of Planning and Environment, 2019; Nairn *et al.*, 2021), heat-related health outcomes are not fully understood at a fine level of spatial granularity. Heat-related illnesses are a spectrum of conditions beyond heatstroke (Jacobson and Raukar, 2020), and only a small number of these may be recorded during any heatwave. Underlying health conditions, such as cardiovascular and respiratory disease, as well as mental illness may be exacerbated during heat events but may not be associated with heat when assessing an event's impact. Deaths that occur during heatwaves may not be reported as heat-related if the cause of death was attributed to an underlying health condition that worsened during high temperatures (Doctors for the Environment Australia, 2020). The process of capturing administrative health data also varies across jurisdictions and typically only one condition, the most severe, is recorded when a patient is admitted to a hospital's emergency department. As a result, cases in which chronic health conditions deteriorate due to excessive heat may only capture half the story, potentially missing out on recording conditions directly associated with heat.

Accessing person-level linked health data for research purposes typically involves a lengthy and complex application process. Due to the sensitive nature of the data, access is restricted and limited to relatively coarse levels of spatial detail, such as Statistical Area 2 (SA2) or above, in order to obfuscate an individual's location information to reduce the risk of identification (Damiani, 2014). While existing heat vulnerability indicators often rely on such aggregated health data (Loughnan *et al.*, 2013) or SA2-level linked data (Physical Environment Research Network, 2021), the resultant spatial detail may be insufficient to fully understand the effect of heat on human health, potentially limiting the utility of resulting indicators. If more detailed analysis can be performed at a finer spatial scale, such as SA1, it should be feasible to explore the complex spatial relationships and patterns associated with heat vulnerability, potentially resulting in the design and delivery of more effective interventions and actions.

Furthermore, built-up areas and urban morphology are important factors that contribute to increased temperatures and population heat stress (Loughnan *et al.*, 2013; CRC for Water Sensitive Cities, 2016). Urban density, morphology and building volume contribute to the intensity of the urban heat island effect (Li *et al.*, 2020). Urban areas with high-rise buildings tend to have a lower sky view factor and higher air temperatures. Surface roughness and) porosity have been demonstrated to affect urban temperatures (Park *et al.*, 2017). High urban density, in conjunction with low vegetation has been associated with higher land surface temperatures and increased population vulnerability (Loughnan *et al.*, 2013). Additionally, the type of landcover can also influence temperatures, with built up areas with low sky view factor (SVF) presenting increased temperatures, whereas waterbodies, wetlands and vegetated areas have the ability to reduce temperatures during the day (CRC for Water Sensitive Cities, 2016). Therefore, it is necessary to include a detailed analysis of urban form and natural environment within heat health vulnerability analysis to better understand the complex relationship between factors that can exacerbate or mitigate the effects of heat on urban population health.

Methodology

Indicator Framework

An SA1 level HHVI pilot project was developed based on the Intergovernmental Panel on Climate Change (IPCC) 2014 framework (Cardona *et al.*, 2012) to assess the risks of extreme events driven by climate change on population health.

HHVI is the sum of weighted scores for sensitivity, exposure and adaptive capacity to heat represented in the form of *sub-indicators* (Figure 1) that combine to create the outcome of the heatwave event or hazard. Sensitivity refers to characteristics of the population that influence the risk of suffering from heat exposure such as socio-economic (living conditions, employment, education), demographic (e.g., age, sex) and health conditions (e.g., comorbidities obtained from linked data) (Loughnan *et al.*, 2013; Hughes *et al.*, 2016; Nicholls *et al.*, 2017) (PEAN, 2021). Exposure refers to characteristics of the built environment such as building height and density, sky view factor, and impervious surfaces that can exacerbate the response to heatwaves (Park *et al.*, 2017; Li *et al.*, 2020). Adaptive capacity refers to the characteristics of the natural environment that mitigate the effects of heat such as vegetation and water coverage (CRC for Water Sensitive Cities, 2016; Pfautsch and Rouillard, 2019).

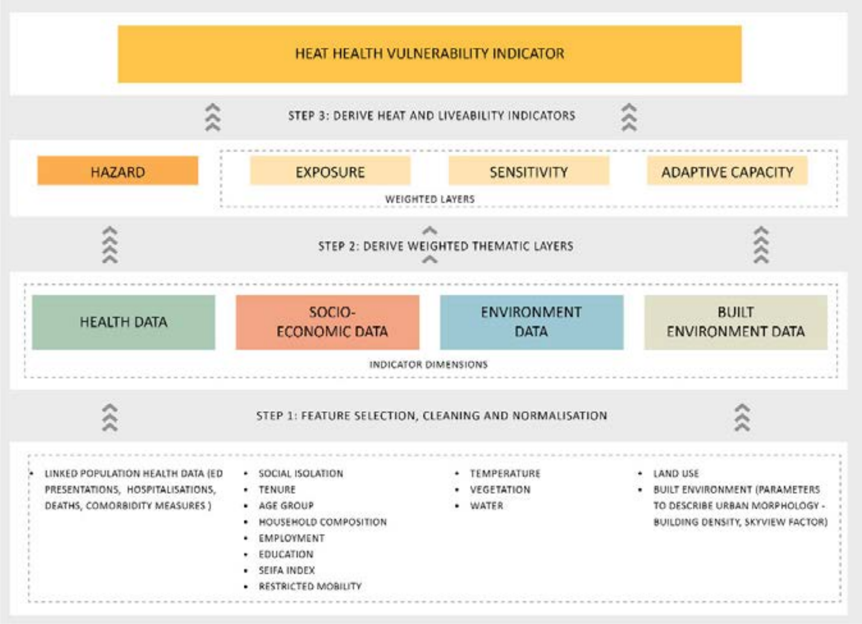

Figure 1. Heat health vulnerability indicator (HHVI), sub-indicators and parameters

Data Analysis Approach

The study uses person-level, deidentified linked health data to ascertain the number and cause of hospital emergency department (ED) presentations, hospitalisations, and deaths during a heatwave. The methodology comprises of the following steps:
1. Linked health data is used for the sensitivity sub-indicators health component, considering clinical histories and cause-of-death during non-heatwave periods. The Charlson comorbidity score (Holman *et al.*, 2005) and specific medical conditions are determined using a 10-year look-back for hospitalized patients. Statistical methods, such as latent class analysis and principal component analysis, help identify correlated variables, reducing collinearity and retaining only the most influential and dependent variables for each sub-indicator.

2. Each variable is normalised to a value between 0 and 1 which allows a comparison between multiple types of variables with different scales of measurement. The normalised values or categories are summed to generate a sub-indicator score, which is normalised to a value between 0 and 1.

3. The three sub-indicator scores together with the hazard layer (which describes the intensity of heat and heatwaves using land surface temperature and excess heat factor data (Figure 1) are–entered into a Poisson multivariable regression to estimate the number of ED presentations, hospitalisations or deaths from the linked health data.

4. The sub-indicator weights from the Poisson regression are used to calculate the HHVI score at the SA1 level:

$$\text{HHVI score} = \beta 1(\text{sensitivity}) + \beta 2(\text{adaptive capacity}) + \beta 3\ (\text{exposure}) \qquad (1)$$

5. To address data privacy and statistical stability issues for the data, smoothing techniques will be applied in situations such as for study areas with small number of cases. Spatial smoothing reduces any risk of identifiability for specific individuals while reflecting the real differences in the underlying rate or risk between areas without presenting actual personalised data.

6. The resulting HHVI expresses the 'relative' vulnerability of locations across the chosen study area. To investigate statistically significant locations of heat health vulnerability, hotspot analysis is performed to generate a Z-score and corresponding P-value spatial fields, to which significance testing can be applied.

Indicator Framework Workflow

Heath data will be securely linked by the New South Wales Data Linkage Unit and ingested to the Secured Unified Research Environment (SURE) virtual workspaces (Figure 2). The rest of the data will be pre-processed in Stage 2 and then ingested into SURE. The ingestion process will be done through transmitting the data to SURE custodians. Once they review and approve it, they will then carry out the ingestion. Access to SURE requires authentication and anti-virus measures. Only approved researchers can access linked unit record data. Non-sensitive data will be pre-processed outside the secure environment and then analyzed in SURE alongside linked health data to streamline data processing. Data at the SA1 level will not be released; only SA2 level data will be approved for release. Findings will be disseminated on websites of the participating organizations of the project after being approved by health data custodians who provides the health data, in order to prevent identification of individuals, practices, or hospitals. Unit record data will be archived in SURE for 7 years after publication and then destroyed, while aggregated results will be stored indefinitely.

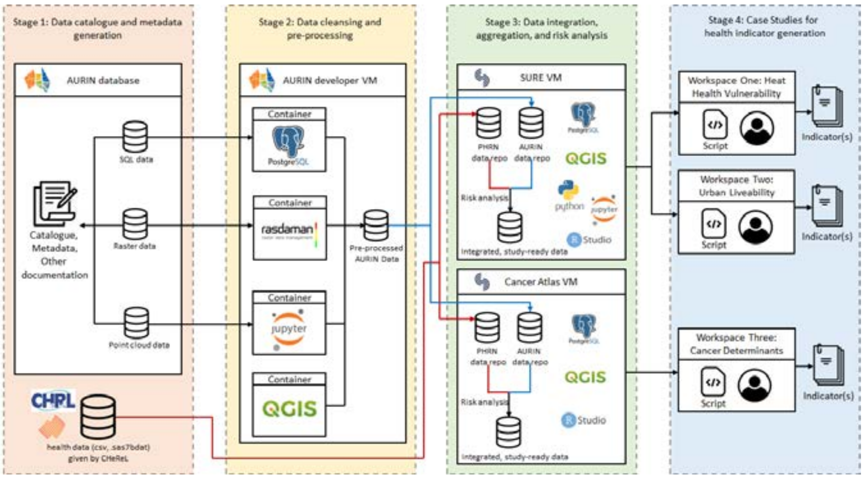

Figure 2. Systems diagram of the secure environment

Identification of Heatwave Periods

The Bureau of Meteorology defines heatwaves as unusually high minimum and maximum temperatures that persist for 3 or more consecutive days at a certain location (Bureau of Meteorology, 2023). Daily land surface temperature (LST) data from the Bureau of Meteorology and Google Earth Engine satellite imagery will be used to identify heatwaves at a fine spatial resolution. The excess heat factor (EHF) (Nairn and Fawcett, 2014) will be employed to identify heatwave days. EHF was proposed as a new index for monitoring and forecasting heatwaves in Australia. Based on a three-day average daily mean temperature (DMT), the EHF captures heatwave intensity relevant to human health outcomes and has potential for international use.

A threshold is applied to the EHF values, such as the 90th percentile, to identify heatwaves and analyze them over time across the study area(s). Lastly, linked health data (ED presentations, hospitalisations, and deaths) is used to examine population sensitivity to heat during spring-to-summer months when extreme heat is more likely to occur. An example of a daily maximum land surface temperature data slice on a specific day for the whole Australia is shown in Figure 3.

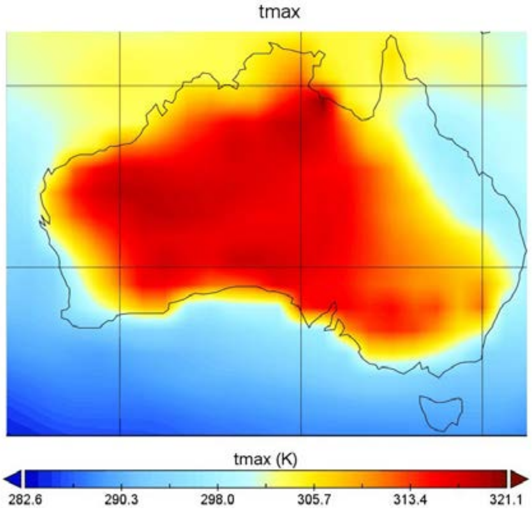

Figure 3. Example of a daily maximum land surface temperature data slice on a specific day for the whole Australia, visualized using Panoply, a data cube visualization tool.

Built Environment

To better understand the morphology of the built environment, a 2.5D city model is created to serve as a basis to derive parameters of urban form that are associated with the urban heat island effect. LiDAR point cloud elevation data from NSW Spatial Services is used to identify the average building height and extrude building footprint polygons from Microsoft and Australian Housing Data Analytics Platform (AHDAP) data, as shown in Figure 4.

Built environment parameters such as building volume, density, skyview factor, surface roughness and porosity are used to describe the urban morphology which are calculated from the city model and are used to identify urban patterns that have the potential to exacerbate heat and increase the urban heat island effect. The built environment parameters are included in the exposure sub-indicator of the HHVI.

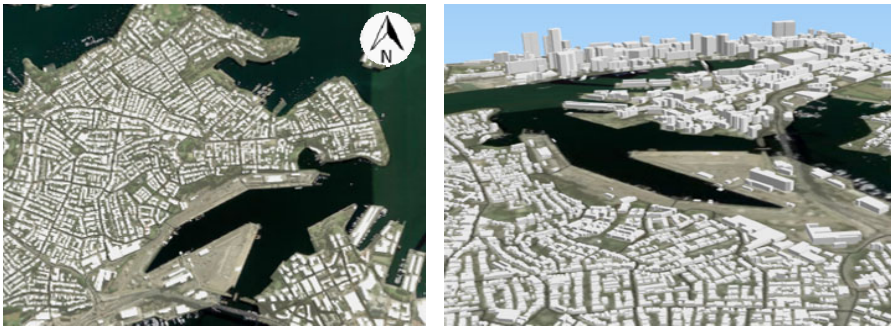

Figure 4 Left: Microsoft Building footprints polygons in Sydney CBD area. Right: Extruded city model using Microsoft building footprints and NSW Spatial Services LiDAR point cloud data.

Land Cover

Landcover data from Digital Earth Australia (DEA) at a 25m resolution for multiple years is used to assess the percentage of vegetation and artificial surface cover for individual SA1 areas. Artificial surface cover is used as a proxy measure for impervious surface and is included as a parameter in the Exposure sub-indicator as it has the potential to increase the urban heat island effect in densely built-up urban areas. Water along with woody and herbaceous vegetation cover are used as parameters for the Adaptive Capacity sub-indicator as they have the ability to reduce heat and counter the negative effects of urban heat islands on human health. Figure 5 illustrates landcover data for the city of Sydney, showing varying proportions of built up and vegetated areas that are used in the HHVI to assess vulnerability to heat.

Figure 5: Landcover data for Sdney suburbs using DEA Landcover and ABS SA1 boundaries.

Discussion

The novel aspect of the HHVI case study is the use of unit level population linked health data with built and natural environment, socioeconomic, demographic and climate data to produce a new and improved understanding of heat health vulnerability at a finer granular level of spatial detail (SA1), capturing spatial patterns that would be averaged out at a coarser level of analysis (e.g. SA2 or above).

The urban morphology analysis identifies building form and distribution patterns that affect the exposure to urban heat, distinguishing between different urban typologies, such as dense high-rise buildings in Sydney's CBD area and low-rise, compact inner suburb development (as shown in Figure 4). Additionally, landcover data is used to assess the level of impervious surface, vegetation, and water cover, which play an important role in exacerbating or mitigating urban heat. As can be seen from Figure 5, western suburbs present densely built areas that are susceptible to be more affected by extreme heat events than areas with high vegetation cover, such as the eastern suburbs.

The use of linked health data to examine health outcomes and comorbidity allows researchers to assess the impact of heat on human health, as well as the likeliness of a patient to suffer during extreme heat events based on the history of medical conditions and previous number of hospitalisations.

Access to restricted linked patient health data is a lengthy and complex process that varies depending on the corresponding jurisdiction in Australia. For this project, data from the New South Wales Ministry of Health was employed, as it was the only state able to provide SA1-level data.

Once a project receives approval from data custodians and the Ethics committee, the Centre for Health Record Linkage (CHeReL) links data from multiple databases and releases it into SURE. Researchers then load the analysis code and other datasets into the environment to perform the analysis. Linked SA1 data cannot be extracted from the SURE environment, and only the resulting spatial indicator will be extracted and published on websites of the participating organizations of the project.

One major limitation of this study is that patient privacy and minimising the risk of reidentification are imperative to the release of linked health data. The NSW Ministry of Health deidentifies unit-level data and patient address is geocoded to Statistical Area Level 1 (SA1) before it is released to researchers. However, the address only contains the street name without the corresponding property number. Therefore, patients may be assigned to a neighbouring area if the street crosses two or more SA1 areas. This may have implications for the accuracy of this study as it could lead to attributing health outcomes to another area.

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