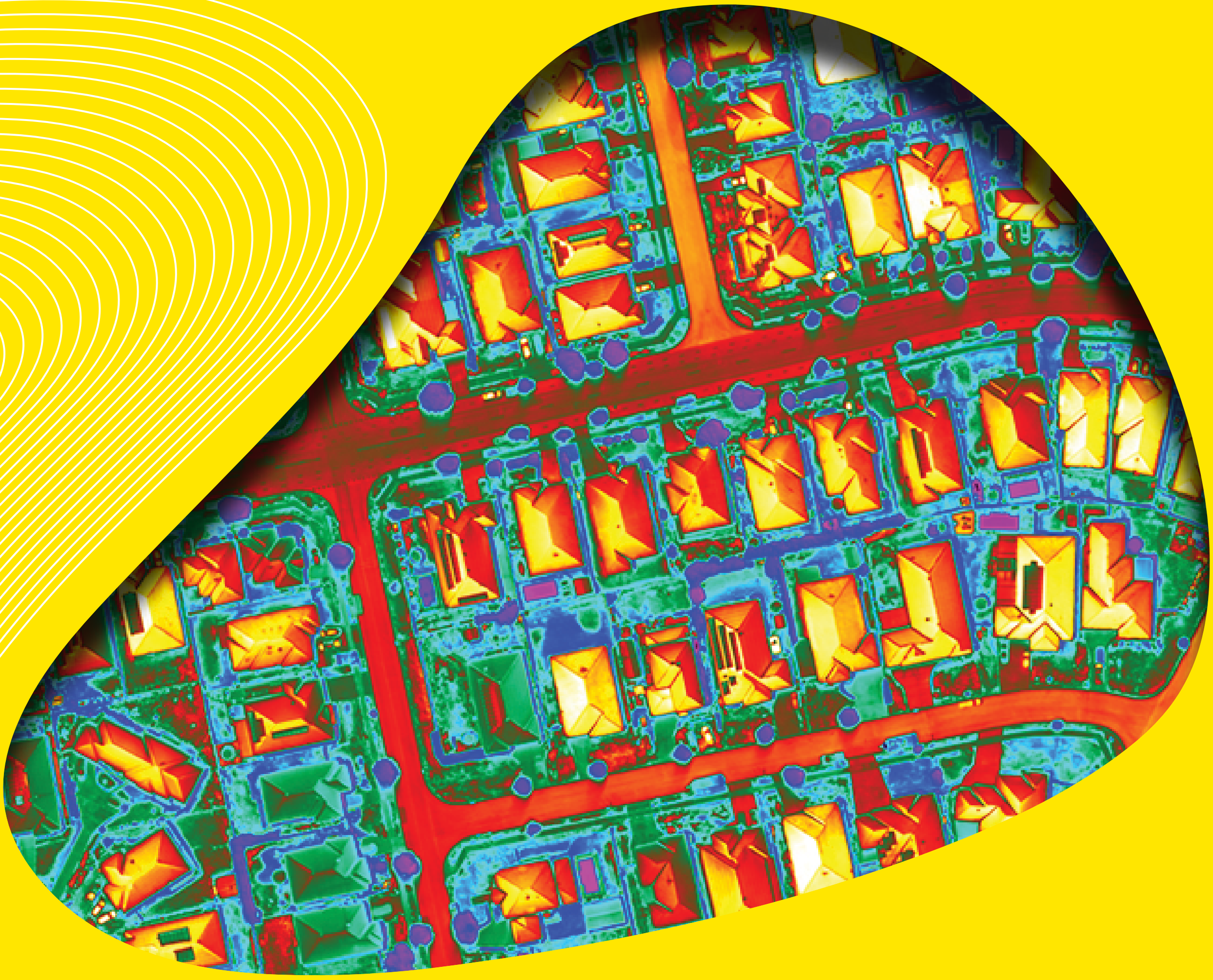
Smart & Cool
Places Phase 1
-
Final Project
Report

National Heat Vulnerability Observatory



NSW GOVERNMENT Planning & Environment

UNSW SYDNEY

DUBBO REGIONAL COUNCIL

maitland city council

Executive Summary

The impacts of urban overheating and heat vulnerability are acknowledged as significant issues for the future of Australian cities across all levels of government. These impacts encompass not only outdoor thermal comfort but also human health, energy and water consumption, equity issues such as access to air conditioning for low-income people, and business and economic development. There are currently a wide range of mitigation and adaptation interventions that can be used to reduce these impacts. Various definitions of heat vulnerability indices are also available, primarily focusing on a single indicator such as population health. However, there is a lack of:

- A nationally consistent and robust approach to measuring and reporting urban heat vulnerability issues across cities in Australia.
- An expanded scope that defines diverse key performance indicators to measure the heat vulnerability performance of cities or precincts.
- An ability to link mitigation and adaptation strategies with a heat vulnerability index that can represent the effectiveness of cooling interventions as potential changes in heat vulnerability to support decision-making.
- A smart data-drive approach providing a central data repository to support smart data analysis and interoperability, increasing digital capability to adapt to future smart cities.

As a result of the existing limitations, it can be extremely difficult for state and local governments to make informed and evidence-based planning decisions to effectively reduce the impacts of extreme heat in Australian cities.

The National Heat Vulnerability Observatory (NaHVO) Phase 1 Smart and Cool Places project is a partnership between the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) and UNSW Sydney. It received a co-contribution from the Smart Places Acceleration Program, part of the NSW Government Digital Restart Fund. This project aims to fill the identified gaps by developing a NaHVO Index that enables a consistent and robust approach to measuring and reporting urban heat vulnerability issues in Australian cities. The NaVHO Index has an expanded scope to cover in-depth built environment characteristics linked with cooling intervention opportunities and diverse key heat vulnerability performance indicators related to environmental, human health, and energy consumption impacts. It is built upon heat vulnerability evidence and benchmark datasets from local urban contexts and can change over time.

Additionally, a smart data-driven approach is developed for the NaHVO data repository and interoperability, providing data collection protocols, and facilitating future connections to government platforms and various applications. Project outcomes will develop a digital capability in NSW and increase the state's resilience to urban overheating. Maitland City and Dubbo Region are two pilot cities in Phase 1 of the NaHVO. The long-term goal is to establish a national heat vulnerability observatory that will be rolled out across Australia.

This report presents project outcomes from Phase 1. It comprises an Introduction to urban heat vulnerability issues, existing studies, and the aim and scope of NaHVO Phase 1, followed by technical reports A, B, C and D, as well as heat mitigation and adaptation recommendations, and directions for Phase 2. A summary of each part is as follows.

Report A

Report A presents the NaHVO Index framework, describing its unique features, its assessment engine, benchmark datasets and evidence, and application examples from the two pilot cities. The NaHVO Index framework encompasses diverse key influential factors and multidisciplinary heat vulnerability performance indicators. Statistical analysis methods and regression models are developed to identify the complex relationships across these key influential factors and key performance indicators to establish the NaHVO Index. The NaHVO Index collects in-depth local built environment data, heatwave information, and socio-demographic characteristics, making it tailored to local urban contexts. The more case study cities or precincts involved, the more robust the NaVHO Index values will be. Additionally, the NaHVO Index is linked with cooling intervention opportunities, making it dynamic and capable of estimating potential reductions in heat vulnerability resulting from mitigation and adaptation strategies.

Report B

Report B presents the Maitland City case study which demonstrates the cooling potential of heat mitigation strategies. Analytical modelling and simulations are conducted at both meso- and micro-scales for the entire Maitland City and three case study precincts—Aberglasslyn, Chisholm and Gillieston Heights—each with unique built environment and socio-demographic characteristics. Local hot spots and heat vulnerability challenges are identified, and mitigation and adaptation strategies are applied to analyse the cooling potential. Aberglasslyn is used for an in-depth analysis of the cooling potential of individual and combined mitigation strategies. Additionally, an energy saving analysis is conducted by applying cool roofs to buildings in Aberglasslyn, Maitland City. The effectiveness of these mitigation strategies will inform potential changes in the NaHVO Index.

Report C

Report C presents the Dubbo Region case study which demonstrates the cooling potential of heat mitigation strategies.

Analytical modelling and simulations are conducted at both meso- and micro-scales for the entire Dubbo Region and two case study precincts—Southlakes and South Dubbo—each with unique built environment and socio-demographic characteristics. Local hot spots and heat vulnerability challenges are identified, and mitigation and adaptation strategies are applied to analyse their cooling potential. Southlakes is used for an in-depth analysis of the cooling potential of individual and combined mitigation strategies. Additionally, subdivision scenarios for the new development in Southlakes are analysed in combination with mitigation strategies to inform future development and planning controls. The effectiveness of these mitigation strategies, along with the subdivision scenarios, will inform potential changes in the NaHVO Index.

Report D

Report D presents a feasibility study of data interoperability for the NaHVO Index and benchmark datasets to enable a smart, data-driven approach to measuring and reporting heat vulnerability issues across cities. It offers an ontology-based framework for representing comprehensive heat vulnerability datasets with their interrelations, as established in Report A. It provides data collection protocols, including data categories, sources and processes, to facilitate a consistent approach to establishing NaHVO benchmark datasets for more cities in Australia. Additionally, it provides a preliminary NaHVO data structure that supports various views for connections to other government platforms, along with examples of connections to the NSW Digital Twin platform. This will broaden the usage of the NaHVO by adding its functions to diverse government platforms and various applications, thereby greatly benefiting governments, industries, and communities.

Recommendations

This section provides key recommendations regarding heat mitigation and adaptation strategies for Maitland City Council and Dubbo Regional Council. These recommendations consider broader mitigation and adaptation strategies as well as those tailored to the local urban contexts in Maitland City and the Dubbo Region. They include:

- Increase tree canopy coverage
- Improve the amenity of green open spaces
- Apply cool and permeable surfaces for streets and paved areas
- Prohibit dark roofs for new developments
- Maintain and encourage shading and water misting along key pedestrian routes
- Increasing housing density must integrate a combination of mitigation strategies
- Establish a network of community heat refuges
- Enhance heat education, awareness, and preparedness

Directions for Phase 2

This section provides a summary of NaHVO's foundational elements and methodology developed in Phase 1, the outcomes of a Government User Needs Workshop conducted in May 2024, and directions for Phase 2 of NaHVO development. The scale-up plan aims to benefit more cities in Australia and minimise the impacts and risks of extreme heat in communities.

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Introduction

The Impacts of Extreme Heat

The annual global average temperature in 2023 reached 1.48 °C above pre-industrial levels, which is the hottest year ever recorded on Earth[1]. With these warmer global temperatures, the world will continue to experience extreme weather events and disasters, such as Europe's 2022 heatwave that was estimated to have caused over 61,000 deaths[2]. Heatwaves can be defined as periods of three or more consecutive days that have unusually hot maximum and minimum temperatures compared to the local climate and past weather[3]. The frequency, severity and duration of heatwaves is anticipated to rise with climate change[4, 5], and this increased overheating of our cities can have considerable health, economic, environmental and social consequences. Some of the major impacts of extreme heat include:

Deaths: Between 1900 and 2010, extreme heat events claimed more Australian lives than the total number of deaths from all other natural hazards combined[6]. Globally, the World Economic Forum estimates that by 2050, extreme heat will claim 1.6 million lives[7].

Human health: In addition to heat stroke and heat exhaustion, extreme heat can exacerbate numerous existing health conditions such as autoimmune diseases, mental illness and migraines as well as amplify the risks of heart attacks, stroke, heart failure and preterm and stillbirths[7-9]. This can place considerable pressure on our health and emergency services. For example, during heatwaves between 2011 and 2019, hospitals across NSW experienced a 14% rise in admissions[10].

Economic cost: By 2050, it is estimated that heatwaves will be responsible for $7.1 trillion lost in productivity because it will be too hot to work, which represents 57% of the economic impact of all other weather events[7]. In Australia under a business-as-usual greenhouse gas emissions scenario and current population growth, it is anticipated that the cumulative loss of wealth per person between now and 2100 from extreme heat will be $61,000[11].

Planetary health: The increased frequency and severity of extreme weather events such as heatwaves can significantly degrade the effectiveness of nature-based solutions to climate change, which can then accelerate and compound the impacts of climate change[12].

Extreme heat has a significant impact on human health, especially for vulnerable populations (© [Getty Images] / iStockphoto).

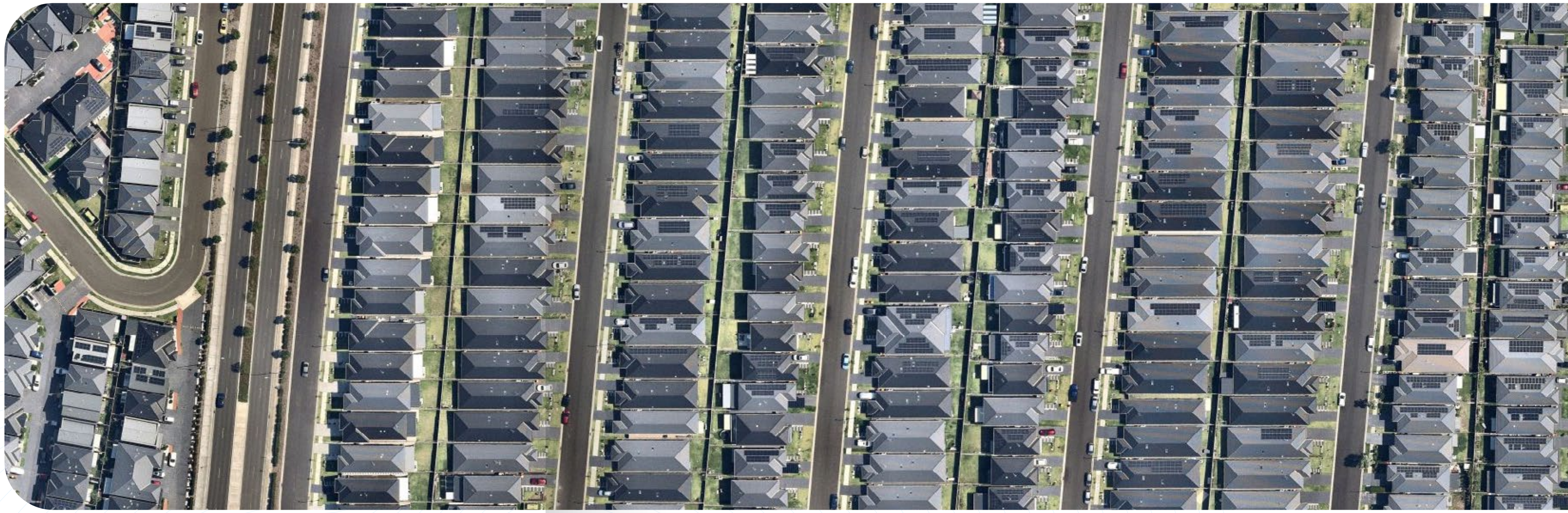
Energy and water consumption: Heatwaves are typically associated with increased energy (total and peak) and water consumption. A reliance on air conditioning for space cooling during heatwaves increases peak electricity demand, and with this an increased risk of blackouts and higher energy bills[13].

Infrastructure damage: Extreme heat can cause significant damage to roads, footpaths, rail tracks, bridges and power lines. During Australia's 2018 heatwave, parts of the Hume Highway literally melted[14].

Education: Classrooms without air conditioning can be associated with reduced learning outcomes for students[15].

Other risks: Extreme heat can also increase the risk of fires, crime and food insecurity, degrade air and water quality, and amplify social issues and vulnerabilities[16, 17].

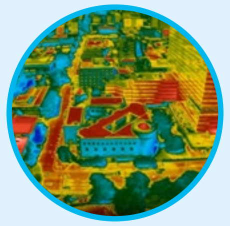
Concerningly, many of the places in Australia that are most vulnerable to extreme heat have been designed without enough of the features that naturally reduce heat such as trees, green spaces and waterways. This exacerbates the urban heat island (UHI) effect—where high-density urban areas have increased ambient temperature compared to surrounding suburban or rural areas—and thereby intensifies the health, economic and environmental impacts of extreme heat for these populations.



The typical housing development typology in Australia can amplify the impacts of extreme heat (Nearmap, 2024).

Existing Heat Mitigation and Adaptation Efforts

Extreme heat is acknowledged as a significant issue for the future of Australian cities across all levels of government. Fortunately, there are now a wide range of mitigation and adaptation strategies that can be used to reduce the impacts of extreme heat that range from nature-based solutions to advanced cooling materials[18]. A growing number of studies have emerged as a result to demonstrate and quantify the benefits of these mitigation and adaptation strategies in areas such as the outdoor thermal environment, energy consumption and human health[19-22]. Currently in Australia, some of the key heat mitigation and adaptation studies and initiatives include:

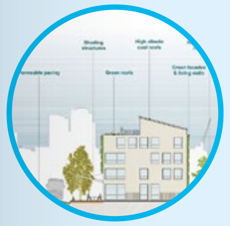


National and international urban overheating mitigation case studies conducted by UNSW's High Performance Architecture (HPA) Research Cluster, including the Cooling Western Sydney[23], Cooling South Melbourne[24], Heat Mitigation in Riyadh[19], and Cool Roofs[25] projects.

UNSW HPA's Urban Heat Island Decision-Support Tool and Index[27], which provides an interactive 3D tool that analyses and visualises the cooling potential of urban heat mitigation options.

The Greater Sydney Heat Taskforce, which is a collaboration across local and state government, industry and the community sector established to coordinate heat-related plans, policies, methodologies and guidelines for Greater Sydney.

The Citizen Science Project, which educates community members about understanding, mitigating and adapting to extreme heat by having them performing outdoor microclimatic measurements[28].



The Guide to Urban Cooling Strategies, which is a design guide for built environment professionals and regulatory agencies seeking to mitigate urban overheating across different urban and climatic contexts in Australia[29].

The urban heat benchmarking studies from Western Sydney University to examine the microclimate variation across local government areas in Western Sydney[30].

The Turn Down the Heat Strategy and Action Plan for Western Sydney led by WSROC and the delivery of multiple projects under this strategy such as the Urban Heat Planning Toolkit and the Cool Suburbs Tool.

Sweltering Cities, which is an NGO that works directly with communities in some of Australia's hottest suburbs to campaign and advocate for more liveable, equitable and sustainable cities.

Amongst many others, these projects and initiatives seek to reduce the impacts of extreme heat in Australian cities but do so at different scales (e.g. neighbourhood, city, region) and levels of detail (e.g. guidelines vs detailed impact analysis), from different disciplines (e.g. built environment, health, policy), and using different methodologies (e.g. modelling and simulation, statistical analysis, qualitative descriptive approaches). Furthermore, many areas that can be most vulnerable to extreme heat such as regional cities and towns are yet to be studied.

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Integrating Mitigation and Adaptation in Heat Vulnerability Assessment

Extreme heat disproportionately impacts vulnerable populations, which consequently widens the gap between disadvantaged and privileged communities[7]. Understanding and assessing heat vulnerability has therefore been an important area of research for the last 15 years[30]. As extreme heat events are becoming more frequent and severe due to climate change, heat vulnerability has also emerged as a key policy and planning priority for all levels of government, especially in Australia[31]. Using the Intergovernmental Panel on Climate Change's (IPCC) definition, heat vulnerability can be understood as the predisposition of communities to be adversely affected by extreme heat based on their sensitivity, exposure and adaptive capacity[32].

It is widely acknowledged that heat vulnerability can be influenced by a range of demographic, socio-economic and environmental factors. As a result, the development of heat vulnerability indexes (HVIs) is a popular way to assess and visualise the spatial and temporal distributions of heat vulnerability across a city. However, many of these existing HVIs have a specific focus on population health without considering a more comprehensive set of influential factors such as in-depth built environment characteristics. They also rarely integrate multi-disciplinary heat vulnerability performance indicators such as outdoor thermal environments, energy consumption, and human health outcomes.

Additionally, existing HVIs rarely incorporate the potential to reduce heat vulnerability through mitigation and adaptation strategies, which can inform urban planning and climate change related decision-making (see Section A.1.2). As a result, Australia currently lacks a nationally integrated and consistent approach to assess and benchmark heat vulnerability, which incorporates the potential of mitigation and adaptation interventions over time. This can make it extremely difficult to make informed and evidence-based planning and policy decisions to effectively reduce the impacts of extreme heat within Australia cities. Responding to these research gaps and challenges poses four key questions:

- How can a holistic understanding of heat vulnerability and its impacts—beyond just population health to include impacts on the thermal environment, energy consumption, and carbon emissions—be translated into an integrated and consistent approach for heat vulnerability assessment and benchmarking in Australia?
- How can the effectiveness of heat mitigation and adaptation strategies be integrated into a national HVI to show a relative change in heat vulnerability?
- What is needed to establish an ongoing and dynamic heat vulnerability assessment that can respond to changes in the local context?
- How can a national HVI be designed for data interoperability to facilitate connectivity with diverse government platforms and various applications?

Aim and Scope of the National Heat Vulnerability Observatory

This project directly responds to these key questions and challenges by establishing a National Heat Vulnerability Observatory (NaHVO). NaHVO aims to provide integrated and consistent assessments of heat vulnerability in Australian cities that integrate the potential to reduce heat vulnerability through mitigation and adaptation strategies. It develops comprehensive heat vulnerability datasets at a national scale, consistent data collection protocols for these datasets, and a robust methodology for the holistic and dynamic heat vulnerability assessment of Australian cities. By doing so, it provides a holistic understanding and assessment of existing heat vulnerability conditions and predicts how this could change over time and in response to targeted heat mitigation and adaptation strategies. To achieve this aim, the NaHVO comprises of four interconnected features (Figure 1):

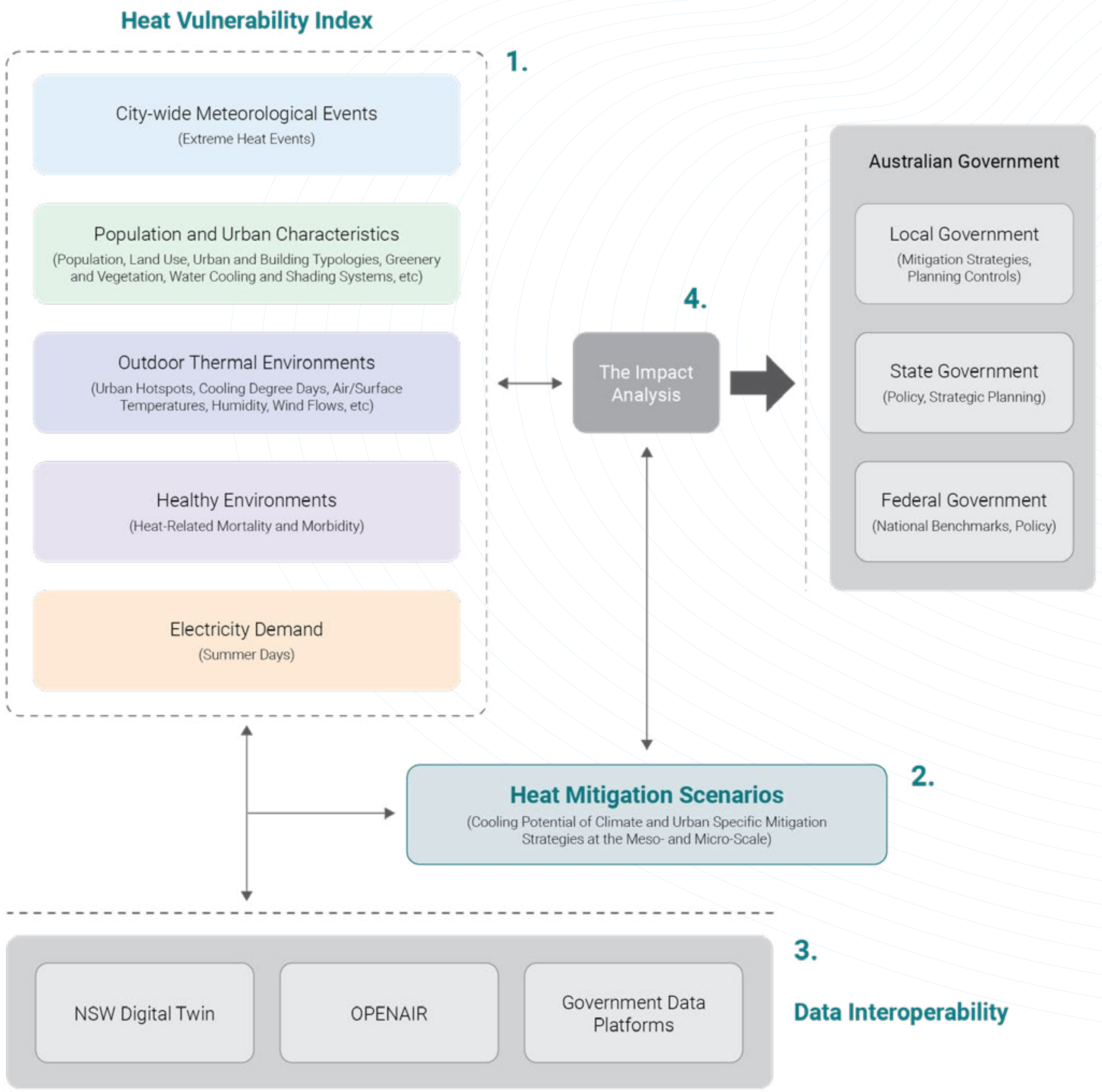

Figure 1. The NaHVO project overview.

1 **The NaHVO Index** provides an integrated, consistent and dynamic heat vulnerability assessment index for Australian cities. It incorporates comprehensive multidisciplinary heat vulnerability benchmark datasets and is underpinned by a robust and scalable methodology. The NaHVO Index also integrates the effectiveness of heat mitigation and adaptation strategies based on in-depth cooling potential scenario modelling and analysis. As such, it provides a holistic and evidence-based method for monitoring and assessing the heat vulnerability of Australian cities (see Report A for details).

2 In-depth modelling and simulation of **what-if scenarios of various mitigation and adaptation interventions** at precinct and city scales. The first phase of the NaHVO, which is the scope of this report, includes a pilot in two regional NSW cities: Maitland and Dubbo. Specific case study precincts within these two cities were collaboratively identified with Maitland City Council and Dubbo Regional Council to assess the effectiveness of targeted mitigation and adaptation strategies that respond to the specific urban context and overheating issues of Maitland and Dubbo (see Reports B and C for details). Importantly, the results of this analysis are integrated with the NaHVO Index to provide a relative reduction in heat vulnerability from the application of mitigation and adaptation strategies.

3 The NaHVO is purposefully designed for **data interoperability**. It provides data collection protocols to establish integrated, consistent, reliable and scalable heat vulnerability benchmark datasets. These datasets (including real-time data), the derived NaHVO Index values and the detailed scenario analysis results can then be integrated with various government platforms and datasets. The scope of Phase 1 of the NaHVO establishes a pilot connection with the NSW Digital Twin (see Report D for details).

4 The NaHVO Index methodology and framework are developed in a way to enable the future integration of advanced **artificial intelligence and machine learning** techniques to enable data-driven decision-making for reducing heat vulnerability in Australian cities. This will also enable the NaHVO Index to make reliable and evidence-based predictions of heat vulnerability under future conditions (see Report A and 'Directions for Phase 2 Work' for details).

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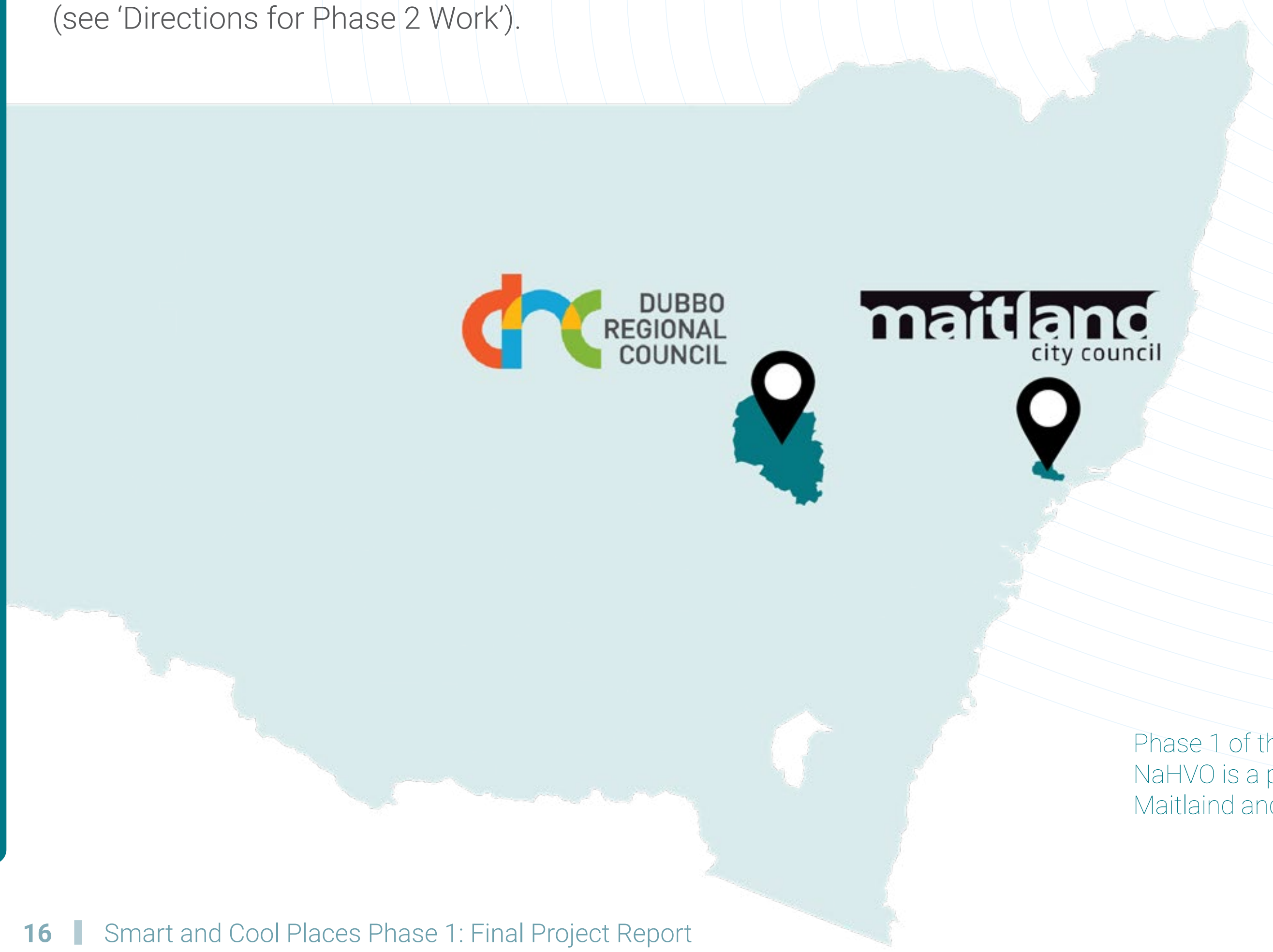
Ultimately, the NaHVO is designed to be applicable to cities and communities across all of Australia. The NaHVO takes a staged approach towards this ambition. Phase 1 of the NaHVO, which is the scope of this report, establishes its foundational elements using Maitland and Dubbo as case study cities. This includes establishing the framework for developing national heat vulnerability datasets and a consistent methodology for measuring and reporting heat vulnerability in Australia. Future phases will then seek to expand to more cities across NSW and Australia. However, the scope of this report includes a scale-up plan for the NaHVO that identifies future directions, opportunities, and considerations for measuring heat vulnerability at a state and national scale (see 'Directions for Phase 2 Work').

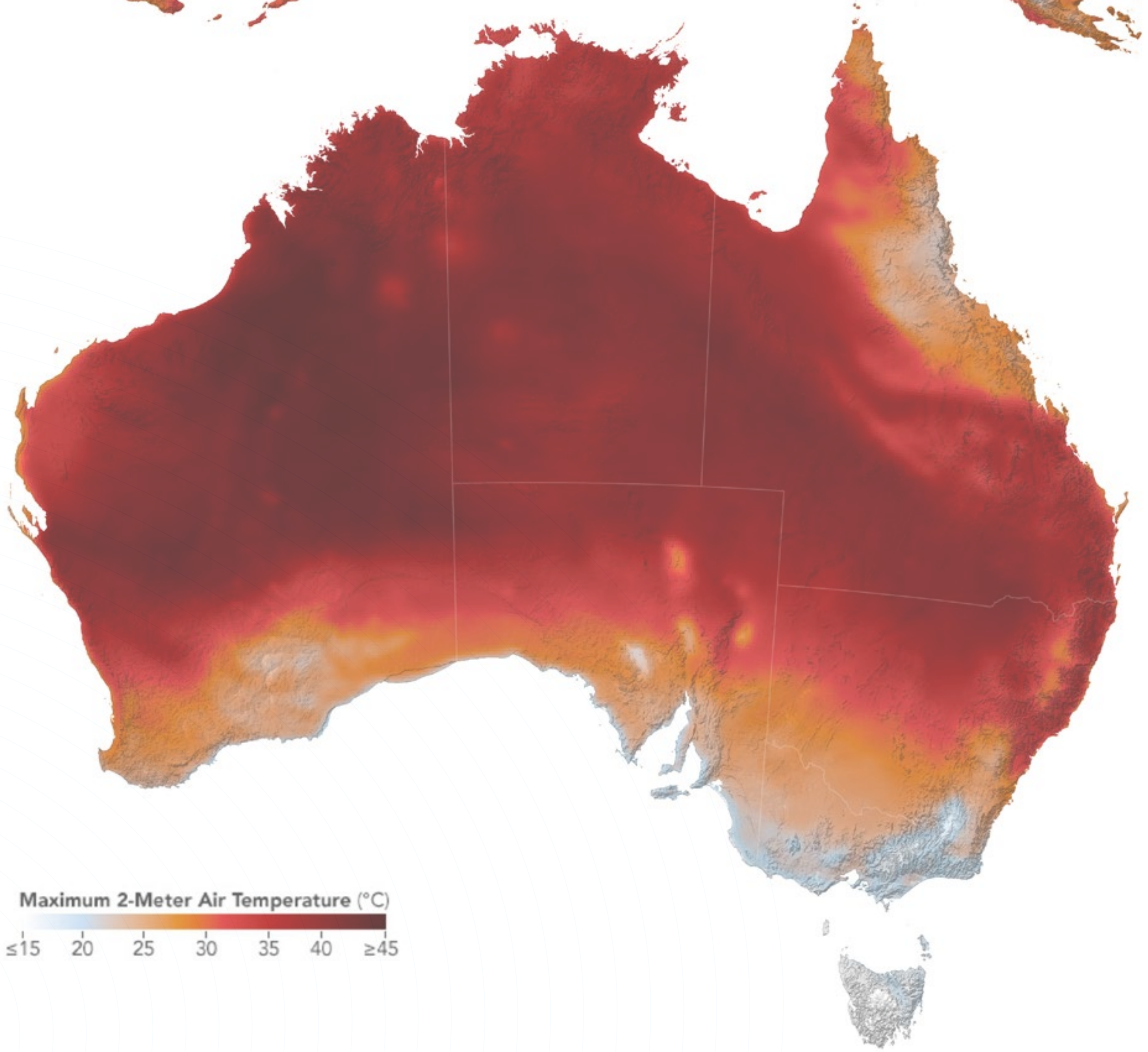
Report Structure

This report presents Phase 1 of the NaHVO as four sub-reports that are aligned with the distinctive features of this project described above.

Report A presents the NaHVO Index and its underlying methodology that provides a reliable and consistent way to benchmark the heat vulnerability of Australian cities. This includes a detailed description of the overall framework of the NaHVO Index and its underpinning heat vulnerability datasets. It also shows the results of the NaHVO Index's application in the two case study cities of Maitland and Dubbo.



Phase 1 of the NaHVO is a pilot in Maitland and Dubbo.

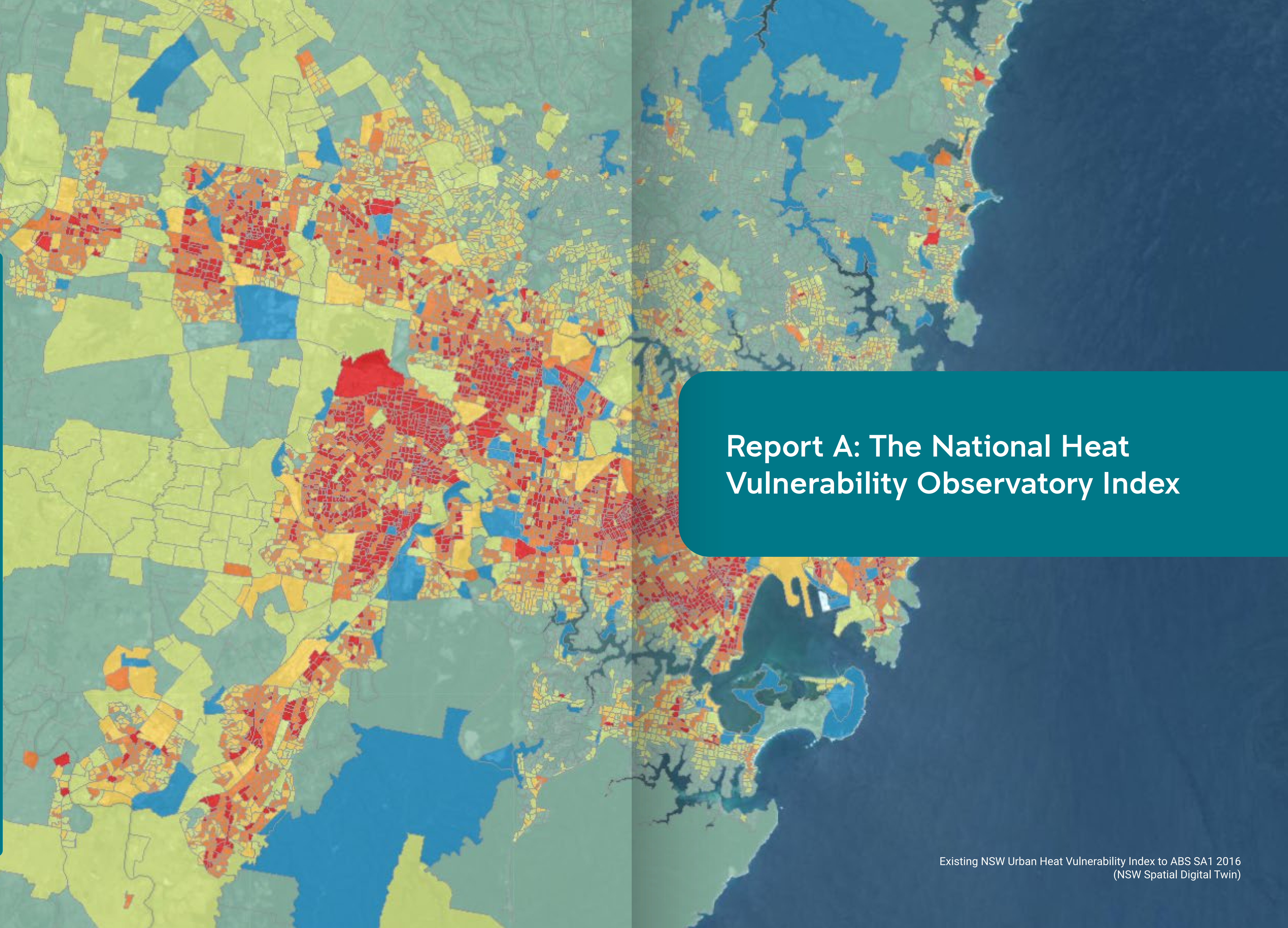


Air temperature distribution across Australia during a heatwave in December 2023 (© [Wanmei Liang] / NASA Earth Observatory).

Reports B and C present the cooling potential scenario analysis of various mitigation strategies for Maitland and Dubbo respectively that are integrated with the NaHVO Index. These reports identify the specific heat vulnerability issues in these two cities, present the detailed analysis results of numerous urban and building scale mitigation scenarios, and provide key findings and recommendations (after Report D) for Maitland City Council and Dubbo Regional Council. The cooling potential scenario analysis results are provided at both the meso- and micro-scale.

Report D presents the data interoperability of the NaHVO. It provides detailed descriptions of the data collection protocols and data structure of the NaHVO to demonstrate its repeatability, scalability and potential integration with other government platforms and datasets. It also outlines the connection with the NSW Digital Twin as part of the Phase 1 pilot of the NaHVO. Finally, 'Directions for Phase 2 Work' presents the scale-up plan for the NaHVO to expand to more cities in NSW and Australia in the future.

Report A: The National Heat Vulnerability Observatory Index



Existing NSW Urban Heat Vulnerability Index to ABS SA1 2016
(NSW Spatial Digital Twin)

A.1 Introduction

A.1.1 Why Do We Need a National Heat Vulnerability Index?

The latest Global Risks Perception Survey in 2023 ranks natural disasters and extreme weather events as the second most severe global risk right now, and suggests that governments are the key stakeholder who can most effectively manage this risk[12]. In Australia, the increasing frequency, severity and duration of extreme heat events continue to have considerable social, environmental and economic consequences, especially for those who are the most vulnerable. As such, heat vulnerability is becoming a key priority for all levels of Australian government. To be able to effectively manage the current and future risks that extreme heat poses, a heat vulnerability index (HVI) can be considered an appropriate approach. This is because HVIs can spatially and temporally determine which areas across a city are most vulnerable to extreme heat based upon comprehensive and multidisciplinary datasets. HVIs can therefore be an effective way to benchmark the heat vulnerability performance of Australian cities.

There are numerous HVIs that have been developed for specific cities and regions around the world. Typically, HVIs are developed in alignment with the IPCC's Risk Framework (Figure A-1). This framework suggests that climate change related risk is determined by the dynamic interactions between *hazards* (occurrence of climate change related events), *exposure* (the extent of people and systems that could be affected) and *vulnerability* (predisposition to be affected based on sensitivity and adaptive capacity)[32]. Many HVIs therefore choose to structure various heat-related indicators directly into categories such as heat exposure, sensitivity and adaptive capacity[33-37].

However, these indexes vary in the methods they use to assess and/or predict heat vulnerability, which can range from relatively simple weighting and ranking methods to more complex statistical methods like regression and principal component analysis. Additionally, many of these existing HVIs are established with a specific scope and purpose, which means there is also significant variation in the heat-related indicators selected and the geographic region they are applied to. While this can be useful for specific end-users of a particular HVI, it can be difficult to develop comprehensive and effective

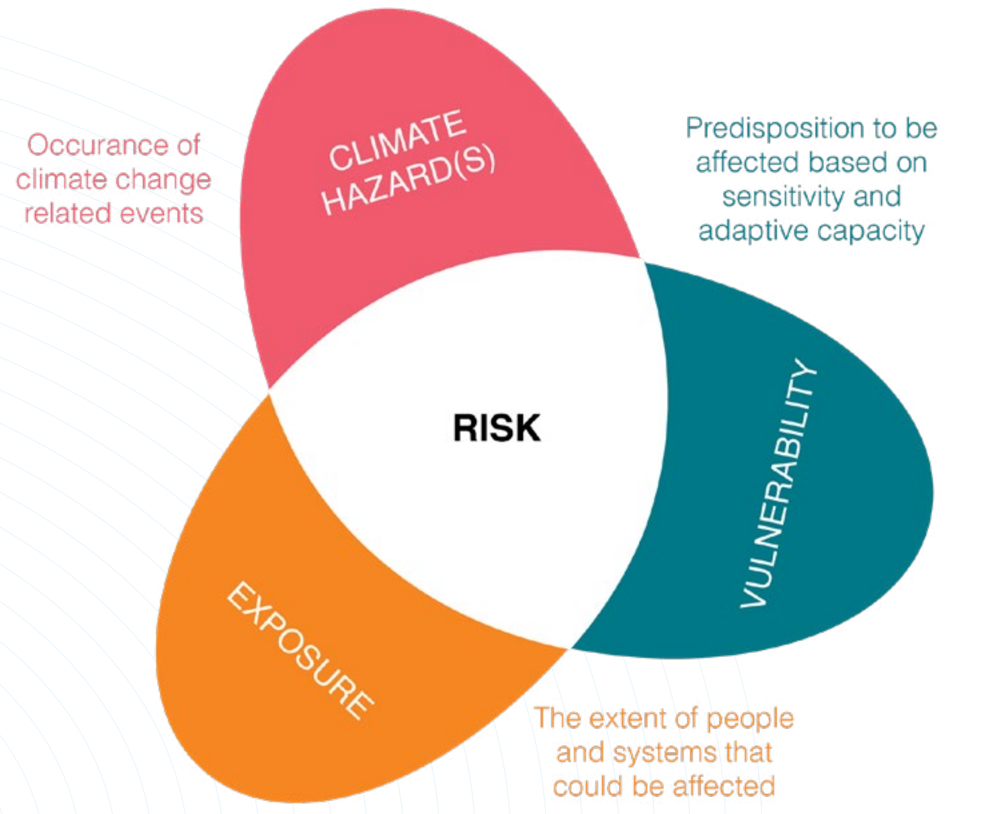


Figure A-1. The IPCC propose that risk can be understood as the intersection of climate hazards, exposure and vulnerability[32].

heat mitigation and adaptation plans with inconsistent heat-related datasets and analysis methods. In particular, the scope of most existing HVIs lacks the integration of in-depth built environment characteristics, which can be linked to mitigation and adaptation strategies to inform urban planning decisions and policy.

To address this, there is a strong need to establish an integrated and consistent national HVI for Australia. Achieving this will require the HVI to be developed from multidisciplinary datasets and underpinned by a methodology that is robust and scalable to large geographic areas. Ultimately, having such a nationally integrated and consistent HVI will enable the heat vulnerability of Australian cities to be reliably reported and assessed. The NaHVO Index presented in this report seeks to establish the foundational elements of developing towards a national HVI for Australia.

A.1.2 What Makes the National Heat Vulnerability Observatory Index Unique?

A review of existing HVIs was conducted to inform how the NaHVO Index could be developed as a nationally integrated and consistent approach for reporting and assessing heat vulnerability for Australian cities. Most relevant to the scope of this project is the 'NSW Urban Heat Vulnerability Index' developed in 2016, which provides a spatial assessment of heat vulnerability for the Sydney Greater Metropolitan Area (includes Newcastle and Wollongong) for the summer of 2014-2015. This NSW Urban HVI integrates land surface temperature with vegetation cover data and socio-economic data from the 2016 Australian Bureau of Statistics (ABS) Census data to provide a heat vulnerability ranking between 1 and 5, which is then mapped to the ABS Statistical Area Level 1 (SA1)[38]. From this review, three key aspects were identified that together make the NaHVO Index a unique and innovative approach to measuring and benchmarking heat vulnerability compared to existing HVIs:

- **Extends the scope of built environment characteristics and performance indicators:**

  Many of the existing HVIs reviewed focus primarily on community and health aspects of heat vulnerability combined with broad land surface datasets[e.g.39, 40]. While this is important, the NaHVO Index extends the scope of heat vulnerability assessment to include in-depth built environment characteristics that can be linked with potential building and urban scale heat mitigation and adaptation strategies. It also extends the scope of heat vulnerability performance indicators to enable an integrated heat vulnerability assessment, which includes outdoor thermal environments, energy consumption and human health (and others in the future). This will support decision-making to reduce heat vulnerability to be based upon a more comprehensive understanding and assessment of heat-related issues.

- **Integrates heat mitigation and adaptation strategies:**

  Existing HVIs predominantly focus on understanding and assessing the heat vulnerability of a city's current conditions. The NaHVO Index integrates a range of heat mitigation and adaptation strategies so that relative reductions in heat vulnerability can be shown from their implementation. This can support future heat vulnerability policies and planning, especially related to informing cooling interventions in the built environment to reduce heat vulnerability.

- **Enables a dynamic assessment of heat vulnerability over time:**

  Most HVIs reviewed also are established to determine the heat vulnerability of a city at a single point in time. However, heat vulnerability is widely understood as something that changes throughout time[32]. The NaHVO Index is designed to be a dynamic assessment of heat vulnerability for Australian cities. Real-time datasets and artificial intelligence techniques will be integrated into the NaHVO Index to demonstrate, monitor and predict how heat vulnerability changes over time. The NaHVO Index also allows the integration of additional datasets to expand how heat vulnerability is understood, assessed and benchmarked in the future.

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A.2 The National Heat Vulnerability Observatory Index Framework

Figure A-2 presents the NaHVO Index Framework, which shows the key and distinctive features underpinning the development of the NaHVO Index. First, a geographical area of interest is defined, which could be a neighbourhood, city or region. As with the existing NSW Urban HVI, the NaHVO Index uses the ABS SA1 boundaries to assess and benchmark heat vulnerability. Within the defined geographic area, the NaHVO Index collects and assesses data for the **key influential factors** that can impact heat vulnerability (see Section A.2.1), and for the **key performance indicators** in which heat vulnerability can be measured (see Section A.2.2). The NaHVO Index assessment engine was developed to statistically understand the relationship between the heat vulnerability key influential factors and key performance indicators, which is explained in more detail in Section A.3.2.

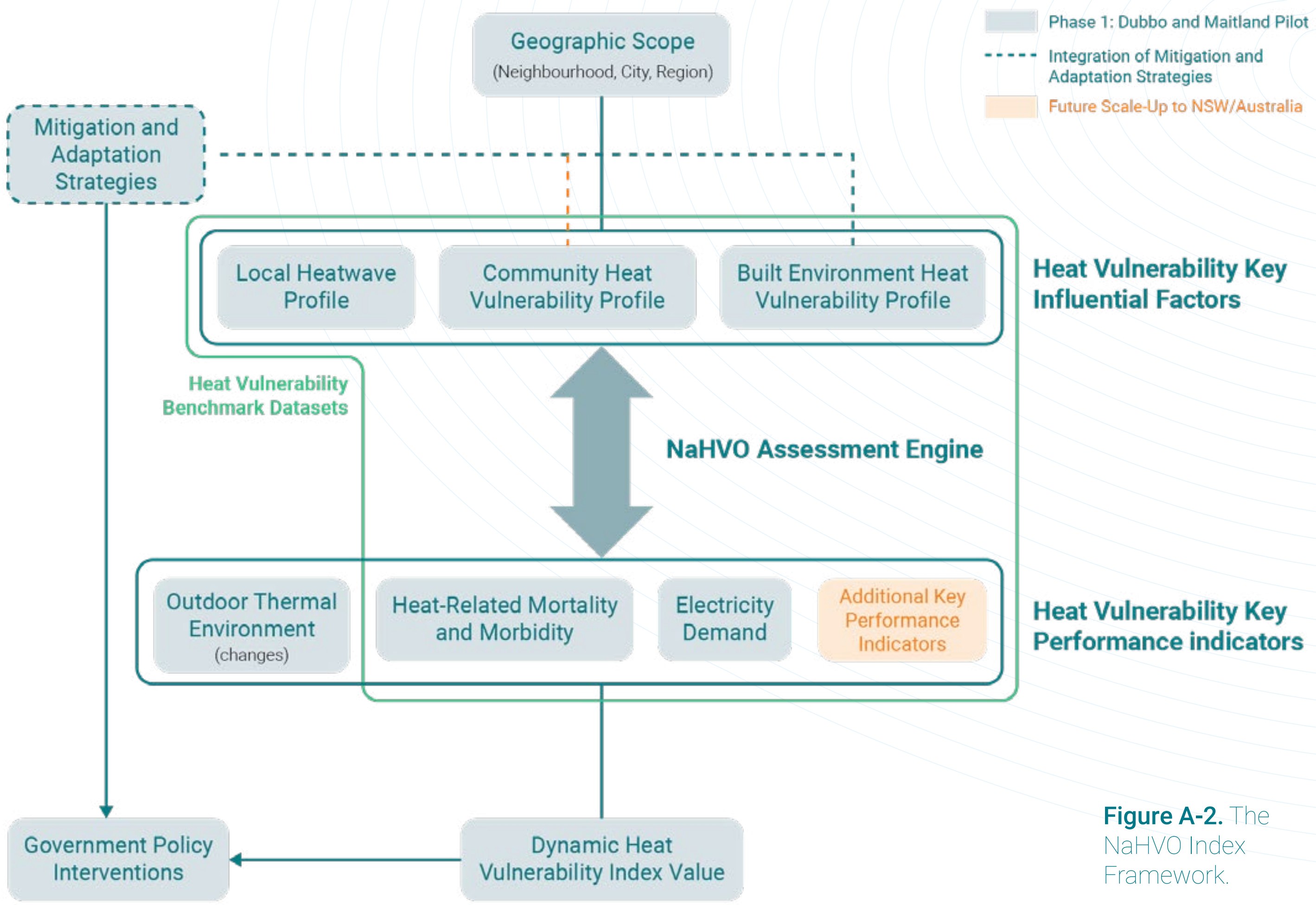

Figure A-2. The NaHVO Index Framework.

A dynamic index value is then generated for each key performance indicator to visually and temporally present the heat vulnerability for each SA1 within the defined study area.

Within this NaHVO Index Framework, the data collected for the key influential factors and key performance indicators form the proposed heat vulnerability benchmark datasets (see Section A.2.3). However, the NaHVO Index also integrates mitigation and adaptation strategies into its assessment of heat vulnerability. This enables the NaHVO Index to provide both an existing heat vulnerability benchmark value and a relative change in heat vulnerability from the implementation of these mitigation and adaptation strategies (see Section A.2.4). These NaHVO Index values for existing and predicted future heat vulnerability can then inform government policy interventions to manage and reduce heat vulnerability. Figure A-2 also shows the scope of what is included in the NaHVO Index for this Phase 1 pilot in Dubbo and Maitland, and what can be included in future phases of the NaHVO Index as it scales up to NSW and Australia (see 'Directions for Phase 2 Work'). Each key feature of this NaHVO Index Framework is explained in more detail in the following sections.

A.2.1 Heat Vulnerability Key Influential Factors

The NaHVO Index defines the key factors that can influence heat vulnerability across three categories—'Local Heatwave Profile', 'Community Heat Vulnerability Profile', and 'Built Environment Heat Vulnerability Profile' (Figure A-2). The key influential factors within these three categories were identified from a review of existing HVIs and heat-related research, such as the urban heat mitigation studies conducted by the UNSW HPA Research Cluster. As mentioned previously, a key distinguishing feature of the NaHVO Index is the integration of in-depth built environment characteristics that are known to influence the impacts of extreme heat, which can inform potential mitigation and adaptation strategies. A list of the specific heat vulnerability key influential factors within each of the three categories is provided in Section A.3.1.

While heatwaves are consistently defined in literature as prolonged periods of unusually hot weather, there are many methods that can be used to determine what is considered unusually hot weather. Common methods include defining an absolute

The NaHVO Index integrates detailed built environment characteristics that can influence heat vulnerability, such as the proportion of hard surfaces, roof materials, and tree canopy coverage. (Nearmap).

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threshold (e.g. >35°C), percentile-based definitions based on maximum and minimum temperatures (e.g. CTX90pct and CTN90pct), and the excess heat factor (EHF)[41]. In Australia, the Bureau of Meteorology (BOM) use the EHF to define the intensity, frequency and distribution of heatwaves. The EHF uses a percentile-based threshold of maximum and minimum temperatures but accounts for the potential acclimatisation of people to their local climate. It also normalises the intensity of a heatwave into a severity classification scheme (low-intensity, severe or extreme)[42]. As such, the **local heatwave profile** of the NaHVO Index uses EHF data to define the frequency and severity of heatwaves for a defined geographic area. More detail regarding the specific datasets used to define the local heatwave profile in the NaHVO Index is provided in Section A.3.1.

It is widely acknowledged that certain communities are more vulnerable to extreme heat than others. In fact, every existing HVI reviewed in this project included a similar range of demographic and socioeconomic factors to determine the heat vulnerability of a given area. A recent review of heat vulnerability assessment methods found that age, economic status, social isolation, education, population density and existing health conditions are among the most frequently used indicators to determine a community's heat vulnerability[43]. Commonly, this demographic and socioeconomic data is derived from national census statistics. The **community heat vulnerability profile** of the NaHVO Index therefore uses 2021 ABS census data at the SA1 level to integrate the key demographic and socioeconomic indicators typically associated with heat vulnerability assessment. A list of the specific indicators used to define the community heat vulnerability profile in the NaHVO Index is provided in Section A.3.1.

The built and natural environment can also have a significant impact on determining the heat vulnerability of a particular geographic area. Detailed characteristics beyond broad satellite-based land use classifications, surface temperatures and simple building information (i.e. density, height, type) are not commonly integrated into heat vulnerability assessments[43]. However, there are many additional built environment factors that can influence the heat vulnerability of specific areas such as the material properties of roads, pavements and roofs. For example, dark roof materials with lower solar reflectivity and thermal emissivity can result in higher indoor temperatures, which can be associated with higher risks of heat-related illnesses and deaths, especially for low-income households that do not have or cannot afford to operate air conditioning[25]. The **built environment heat vulnerability profile** for the NaHVO Index therefore includes more built environment characteristics than many existing HVIs. This enables the NaHVO Index to be integrated with heat mitigation and adaptations strategies to show a relative change in heat vulnerability, which is discussed further in Section A.2.4. The list of specific built environment indicators used in the NaHVO Index to define the built environment heat vulnerability profile is provided in Section A.3.1.

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A.2.2 Heat Vulnerability Key Performance Indicators

The NaHVO Index also defines the key performance indicators that can be used to measure the heat vulnerability of Australian cities. Like the heat vulnerability key influential factors, Phase 1 of the NaHVO Index defines the heat vulnerability key performance indicators across three categories— 'Heat-Related Mortality and Morbidity', 'Electricity Demand', and 'Outdoor Thermal Environment' (Figure A-2). However, as the impacts of extreme heat extend well beyond these categories, future phases of the NaHVO Index are likely to integrate additional heat vulnerability key performance indicators such as water demand, air quality and indoor thermal environment (see 'Directions for Phase 2 Work'). The specific datasets for each of the heat vulnerability key performance indicators of the NaHVO Index is provided in Section A.3.1.

Extreme heat in Australia has and continues to cause a significant number of excess deaths compared to other natural disasters[6]. It can have a direct impact on human health through heat stroke and exhaustion as well as more serious indirect impacts on a wide range of existing health conditions[7]. Some existing HVIs have correlated heat vulnerability influential factors with the spatial variation of heat-related heath outcomes[9]. They do so by collecting mortality and morbidity data for specific heat-related medical disease classification codes within defined ABS or health district spatial boundaries. The **heat-related mortality and morbidity** key performance indicator for the NaHVO Index uses existing literature and recommendations from NSW health experts to identify specific medical codes for diseases that are directly and indirectly impacted by extreme heat. More detail regarding the specific datasets used for the heat-related mortality and morbidity key performance indicator in the NaHVO Index is provided in Section A.3.1.

Due to the increasing reliance of air conditioning for space cooling in Australian homes, extreme heat has a significant impact on energy consumption. Extreme heat also impacts the peak electricity demand, which can increase the risks of blackouts and exacerbate heat-related health impacts. Accordingly, some existing HVIs integrate energy-related heat vulnerability indicators such as the proportion of electricity coverage (in developing countries)[44], the occurrence of power outages[34] and the proportion of homes with air conditioning[45]. However, few existing HVIs integrate energy consumption data into the assessment of heat vulnerability.

Integrating energy consumption in HVIs can help identify hotspots of electricity demand during heatwaves (© [Matthew Henry] / Unsplash).

Therefore, the NaHVO Index defines **electricity demand** as a key performance indicator to determine how vulnerable specific populations are to extreme heat based on their energy consumption. This enables the identification of areas that are using more energy during heatwaves, which has implications for the electricity grid stability and reliability. More detail regarding the specific datasets used for the energy demand key performance indicator in the NaHVO Index is provided in Section A.3.1.

Existing heat vulnerability assessments and HVIs commonly use air temperature, surface temperature and humidity to define the heat exposure of specific areas[43, 46-48]. As mentioned previously in Section A.2.1, the NaHVO Index defines a local heatwave profile based on the EHF, which is derived from maximum and minimum air temperatures. Local weather data such as air and surface temperature are also integrated into the NaHVO Index's third key performance indicator, **outdoor thermal environment**. However, this key performance indicator only relates to the relative change in heat vulnerability from the integration of various building and urban-scale mitigation and adaptation strategies (see Section A.2.4 for more detail). This involves both actual local weather data and predicted values from mitigation scenario analysis simulations for the case study precincts in Maitland and Dubbo (see Reports B and C). As outlined in Section A.1.2, this addresses the current research gap, as few existing HVIs integrate the potential for relative improvements in heat vulnerability based on the application of mitigation and adaptation strategies.

A.2.3 Heat Vulnerability Benchmark Datasets

The heat vulnerability key influential factors and key performance indicators of the NaHVO Index provide an integrated and consistent foundation for determining how heat vulnerability can be measured in Australia cities and identifying what factors contribute to this. For this reason, these key influential factors and key performance indicators represent the datasets required to be able to assess the heat vulnerability of Australian cities: the heat vulnerability benchmark datasets (Figure A-2).

Therefore, the resulting NaHVO Index values are proposed as a way to measure and report the heat vulnerability of Australian cities. Importantly, these benchmark datasets and NaHVO Index values are dynamic to enable the heat vulnerability of Australian cities to be monitored over time in response to changes in their local context (e.g. population density, land use, urban and building surface materials, greenery, etc.) and climatic conditions (e.g. increased number of heatwaves). Establishing heat vulnerability benchmarks also enables the NaHVO Index to explore and quantify how heat vulnerability in relation to each key performance indicator can be improved through mitigation and adaptation strategies.

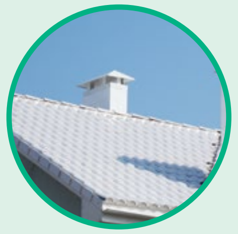
A.2.4 Mitigation and Adaptation Strategies to Reduce Heat Vulnerability

The integration of mitigation and adaptation strategies into the NaHVO Index is one of its key distinguishing features compared to existing HVIs. This enables a relative change in heat vulnerability to be captured by the NaHVO Index in response to different mitigation and adaptation strategies. This, in combination with the dynamic nature of the NaHVO Index, has the potential to support government policy scenario planning. For example, how could the heat vulnerability of a defined area change if tree canopy coverage is doubled under current and 2050 climatic conditions?

Phase 1 of the NaHVO Index includes only mitigation strategies that are linked directly to the specific cooling intervention scenarios of the Maitland and Dubbo case study precincts (see Reports B and C). This means only changes to key influential factors within the built environment heat vulnerability profile are considered. For future phases, more mitigation and adaptation measures will link to community heat vulnerability profile changes (e.g. education initiatives). (Figure A-2). The mitigation strategies investigated by this Phase 1 pilot in Maitland and Dubbo, and integrated into the NaHVO Index, fall into the following categories[25]:

Urban greenery

Increased cooling through evapotranspiration and shading of hard surfaces.



Reflective materials of land surfaces and buildings

Reduced solar absorption with lower surface temperatures and less heat released into the urban environment.

Water technologies

Water irrigation, misting, and fountains.

Shading

Artificial outdoor shading of public areas.

A.3 Methodology

A.3.1 NaHVO Index Datasets

Figure A-3 presents an overview of the benchmark datasets used in the NaHVO Index. The datasets are colour-coded to indicate which datasets were used in the Phase 1 pilot of the NaHVO Index, and which could be included in the future scale-up of the NaHVO Index to NSW and Australia. The NaHVO Index datasets are categorised into the heat vulnerability key influential factors and key performance indicators described previously. These datasets are used in the NaHVO Index assessment engine to establish a dynamic heat vulnerability index value for a defined geographic area, which can then be used to support planning and policy decisions through connections with government datasets and platforms such as the NSW Digital Twin. Figure A-3 also shows the integration of the meso- and micro-scale simulation results for the Maitland and Dubbo case study precincts, which enables the NaHVO Index to provide a relative change in heat vulnerability from heat mitigation and adaptation strategies. Real-time weather sensor and drone survey data is also collected as part of the NaHVO, but its integration with the NaHVO Index calculation will be in future phases.

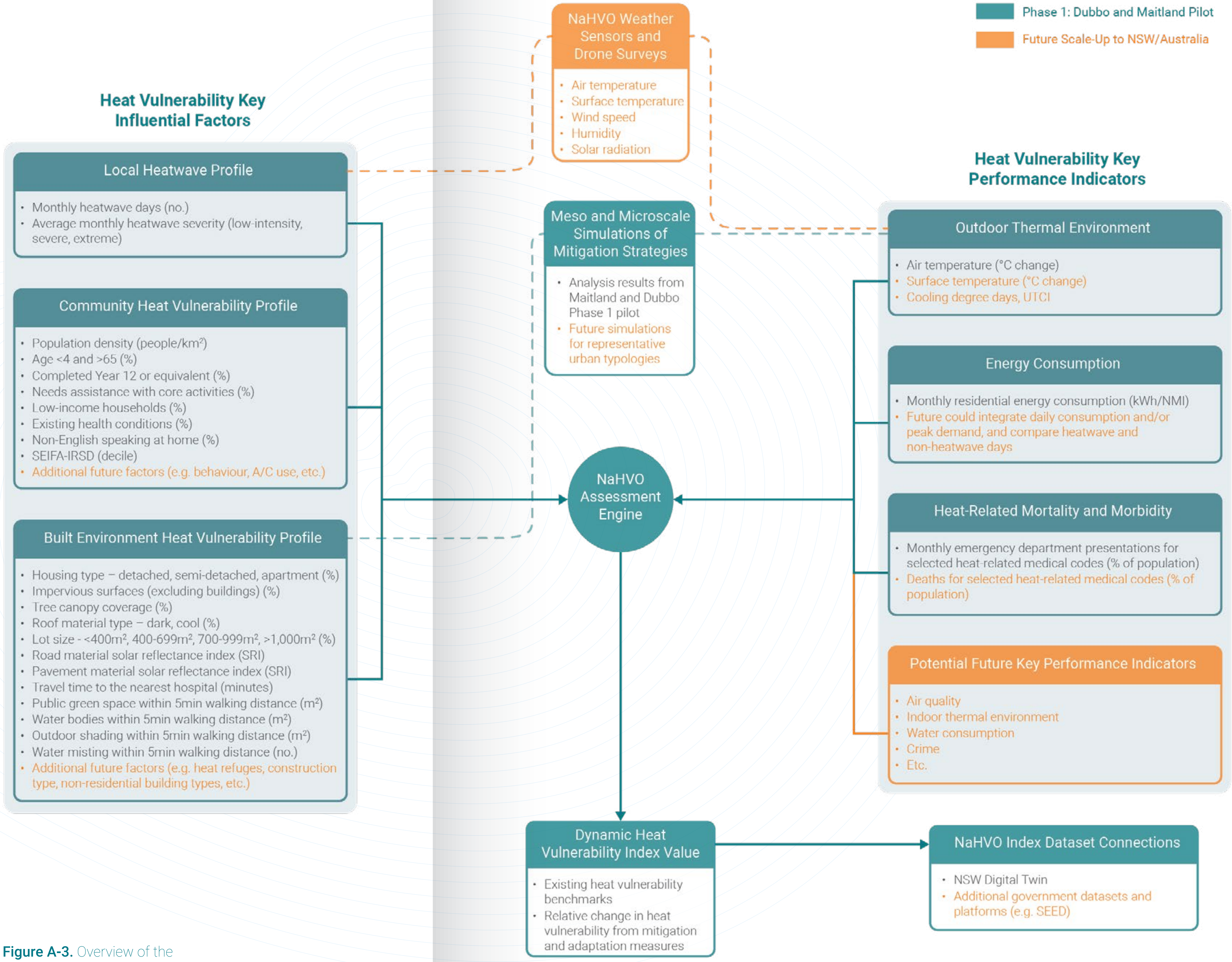


Figure A-3. Overview of the NaHVO Index datasets.

The NaHVO Index datasets are compiled from a wide range of sources. The local heatwave profile uses the BOM EHF data to define the monthly number of heatwaves and their severity. The community heat vulnerability profile uses the 2021 ABS census at the SA1 level for key demographic and socio-economic data, and future phases may include heat-related behavioural data from additional surveys. As mentioned previously, the NaHVO Index includes in-depth heat-related built environment characteristics and this is compiled from data provided by local councils, satellite imagery and open-source datasets. The built environment heat vulnerability profile in Phase 1 only considers similar low-rise residential building and urban contexts due to the selected case study precincts in Maitland and Dubbo (see Reports B and C). Future phases of the NaHVO Index will seek to include a more diverse range of building and urban typologies.

The energy consumption data is aggregated monthly data provided by the NSW Government and energy providers. The scope of energy consumption data for Phase 1 was monthly average residential energy consumption data at the SA1 level, but future phases could integrate daily consumption and peak demand data to distinguish between heatwave and non-heatwave days. The heat-related mortality and morbidity data includes aggregated monthly emergency department presentations at the SA2 level, and this was provided by NSW Health. Specific disease classification codes that are directly or indirectly heat related were identified in collaboration with medical experts. Future phases will seek to include heat-related death data as well. The outdoor thermal environment data relates to the results of the cooling potential analysis for the Maitland and Dubbo case studies. Phase 1 includes changes in outdoor air temperature, but future phases could include additional indicators such as surface temperature, cooling degree days and the Universal Thermal Comfort Index. Future phases of the NaHVO Index will also integrate additional key performance indicators such as air quality and water consumption (see 'Directions for Phase 2 Work').

The scope of the NaHVO Index datasets for the Phase 1 pilot in Maitland and Dubbo is based on monthly heat vulnerability key performance indicator data. The defined study period is between November and March for 2018/2019 and 2019/2020. This is in response to the scope of electricity consumption data available within the timeframe of the Phase 1 pilot project of the NaHVO. More recent summer periods were also excluded to avoid any impacts of COVID-10 on the heat-related emergency department presentations data. More detail regarding the scope of each of the NaHVO Index datasets is provided in Report D.

Heat-related emergency department presentations is a key performance indicator for heat vulnerability in the NaHVO (© [Spiroview Inc.] / Adobe Stock).

Ultimately, the development of the NaHVO Index compiles comprehensive and multi-disciplinary datasets related to heat into an integrated and consistent data observatory for heat vulnerability. These datasets can be used to establish benchmarks for the heat vulnerability of Australia cities, monitor changes in heat vulnerability over time, and predict the potential to reduce heat vulnerability through mitigation strategies. For this reason, it is important to define robust data collection protocols for these NaHVO Index datasets. Report D presents the detailed and technical information related to these data collection protocols and data structure to ensure the NaHVO Index is repeatable, scalable and interoperable.

A.3.2 The National Heat Vulnerability Observatory Index Assessment Engine

The NaHVO Index assessment engine provides an understanding of the relationship between the defined heat vulnerability key influential factors and key performance indicators (Figure A-3). It statistically analyses the NaHVO Index benchmark datasets to determine which key influential factors are the most important for which key performance indicators, and to what extent they influence heat vulnerability performance. A regression model is used to establish this understanding between the key influential factors and each heat vulnerability key performance indicator, which comprise outdoor thermal environments, energy consumption, and heat-related mortality and morbidity. The predicted results for each performance indicator are then ranked to generate heat vulnerability index values. Phase 1 of this project uses benchmark datasets from the case study precincts (see Section A.4) to provide pilot NaHVO Index values for these areas. In future phases of the NaHVO, the more case study precincts that are involved, the more robust these NaHVO Index values will become.

The NaHVO Index assessment engine, using this regression model, can therefore predict heat vulnerability index values based on the key influential factors for any given SA1 area for future conditions (e.g. increased population and heatwaves, changes to demographic and built environment characteristics, etc.). However, it is important to note that the accuracy and reliability of the NaHVO Index results and predictions will improve in future phases with the increased quantity and quality of data inputs. More advanced statistical models may also be needed with this increased scope of data in future phases of the NaHVO Index (see 'Directions for Phase 2 Work').

The NaHVO Index assessment engine comprises of the following steps:

Data collection and processing

The NaHVO Index datasets are collected and processed into a tabular format. More detail on the data collection protocols and processing methods for the NaHVO Index datasets is provided in Report D.

Standardising multidisciplinary datasets

The heat vulnerability key influential factors are standardised to address scale differences in the data. Z-score standardisation was used as it can improve the accuracy of regression models. However, this method assumes the data is normally distributed, which may not be the case for all datasets in future phases. Therefore, as the NaHVO Index datasets expand in size and complexity to cover NSW and Australia, alternative standardisation methods may be required.

Identifying statistically significant variables

For each heat vulnerability key performance indicator—energy consumption, heat-related mortality and morbidity, outdoor thermal environment, and others in future phases—statistical significance testing is conducted to determine which heat vulnerability key influential factors are statistically significant. Due to the relatively small sample size of data in Phase 1 of the NaHVO Index, a statistical significance level of $p<0.1$ is defined. In future phases with more comprehensive datasets, $p<0.05$ or lower may be more appropriate. The key influential factors that are not statistically significant for a given key performance indicator are then removed.

Reducing multicollinearity

Multicollinearity is when two or more of the heat vulnerability key influential factors are highly intercorrelated (i.e. influencing each other), which can cause misleading results. The variance inflation factor (VIF) is calculated for the remaining heat vulnerability key influential factors to address potential issues of multicollinearity. A VIF <5 can be considered acceptable as this shows low to moderate multicollinearity[49]. The key influential factor with the highest VIF is removed until all VIF values are <5.

Multiple linear regression

A multiple linear regression analysis is conducted with the remaining heat vulnerability key influential factors with the associated key performance indicator. A training function for the regression model is defined based on 80% of the data and compared with 20% for testing. The accuracy of this basic machine learning model is determined by the root-mean-squared error (RMSE) and comparing the RMSE of the training and test predictions.

Scaling the predicted outcomes

The predicted results for the given heat vulnerability key performance indicator are then scaled using min/max scaling to provide an index value between 1 and 10. The NaHVO Index results are therefore a relative ranking showing the highest and lowest areas of heat vulnerability. This means the NaHVO Index values will change as more data and geographical areas are included across NSW and Australia.

A.4 Pilot Application of the National Heat Vulnerability Observatory Index

A.4.1 Case Study Precincts

Phase 1 of the NaHVO included a pilot application of the NaHVO Index in two case study areas: Maitland City and Dubbo Region. Within these two areas, five individual case study precincts were identified to pilot the NaHVO Index. These were recognised areas of existing vulnerable populations and future residential growth by Maitland City Council and Dubbo Regional Council. A brief overview of the five case study precincts is provided below but detailed descriptions of their urban characteristics and heat vulnerability challenges are provided in Reports B and C for Maitland and Dubbo respectively.

South Dubbo, Dubbo (above): The South Dubbo case study precinct is an existing residential area south of Dubbo's town centre. It was identified for the Phase 1 pilot of the NaHVO Index as it includes a diverse range of low-rise residential building typologies (detached houses, townhouses, apartments), and has relatively good tree canopy coverage with substantial public green space. There are four SA1 areas within this precinct's defined boundary.

Southlakes, Dubbo (right): The Southlakes case study precinct is a new low-rise greenfield residential development south-east of Dubbo's town centre that is still partly under construction. This precinct was considered for the Phase 1 pilot of the NaHVO Index as it is considered the typical detached housing residential development typology for future growth in Dubbo. It also includes a combination of large and small lot sizes, and Dubbo council were interested in investigating the heat vulnerability impacts of varying residential density to inform future developments. There are three SA1 areas within this precinct's defined boundary.

Aberglasslyn, Maitland (left): The Aberglasslyn case study precinct is a relatively new low-rise residential development north-west of Maitland's town centre. This precinct was identified for the Phase 1 pilot of the NaHVO Index as it represents the typical detached housing residential development typology of future growth in Maitland. There are six SA1 areas within this precinct's defined boundary.

Chisholm, Maitland (right): The Chisholm case study precinct is located south-east of Maitland's town centre. This precinct comprises a combination of existing large residential properties with substantial tree canopy and new low-rise residential development with increased density, which made it an appropriate case study for the Phase 1 pilot of the NaHVO Index. There are four SA1 areas within this precinct's defined boundary.

Gillieston Heights, Maitland (above): The Gillieston Heights case study precinct is located south of Maitland's town centre. This precinct was deemed suitable for the Phase 1 pilot of the NaHVO Index as it contains a diverse mix of old and new residential typologies, including a retirement village. There are five SA1 areas within this precinct's defined boundary.

The Aberglasslyn and Southlakes case study precincts are the two key precincts for Phase 1 of the NaHVO. This is primarily because they represent the typical residential development approach for future growth in Maitland and Dubbo. Aberglasslyn and Southlakes are therefore the primary focus of the cooling intervention analysis to determine the effectiveness of mitigation and adaptation strategies in reducing heat vulnerability (see Reports B and C). Accordingly, these two precincts will be used in this section as examples to demonstrate the key insights from the NaHVO Index datasets and the NaHVO Index results.

A.4.2 Key Insights from the National Heat Vulnerability Observatory Index Datasets

This section provides key insights from the NaHVO Index datasets resulting from the Phase 1 pilot application of the NaHVO Index in Maitland and Dubbo. These key insights are categorised by the heat vulnerability key influential factors and key performance indicators, which are consolidated into a heat vulnerability snapshot. Heat vulnerability snapshots for the Aberglasslyn and Southlakes case study precincts are provided as examples to highlight the key insights from the NaHVO Index datasets.

Aberglasslyn

HEAT VULNERABILITY SNAPSHOT

During the Phase 1 study period, Aberglasslyn recorded the highest maximum air temperature of all case study areas. Generally, the residents of Aberglasslyn are diverse, wealthy, healthy, and younger compared to other Maitland precincts. It has average sized homes with the highest proportion of dark roofs compared to the other case study precincts. Aberglasslyn also has the lowest average tree canopy coverage compared to the other Maitland precincts. Under extreme heat conditions, the NaHVO Index datasets for Aberglasslyn show an increase in residential energy consumption and an increase in the proportion of emergency department presentations.

Local Heatwave Profile:

21 heatwave days in January 2019. It also had the highest maximum temperature of **41.5 °C** in February 2020.

Built Environment Heat Vulnerability Profile:

80% of the lot sizes on average are under 700 m²

6% tree canopy coverage on average – lowest among the Maitland precincts

88% of dwellings have dark roofs – the highest on average among the case study areas

7 minutes average time to drive to the nearest hospital – close to health facilities

Community Heat Vulnerability Profile:

12% are low-income households – this ranges between 5% and 20% for SA1s in Aberglasslyn

27% of residents have one of more pre-existing health conditions – the healthiest on average of the Maitland precincts

10% of residents speak a language other than English at home – the most diverse among the Maitland precincts

17% of residents are at a vulnerable age (<4 or >65) – lowest among the case study areas

Energy Heat Vulnerability:

Had the highest average monthly household residential energy consumption in January 2019. This was almost double the consumption compared to November 2019.

Health Heat Vulnerability:

Its highest proportion of heat-related emergency department presentations was in January 2019, which had a large number of hot days.

Southlakes

HEAT VULNERABILITY SNAPSHOT

During the Phase 1 study period, Southlakes recorded the longest heatwave and the highest number of heatwave days. Generally, the residents of Southlakes are diverse, wealthy, healthy, and younger compared to the other case study precincts. More specifically, its population are the least disadvantaged, have the lowest proportion of existing health conditions, and are the most ethnically diverse. Southlakes includes large single detached houses with the lowest proportion of dark roofs. Its tree canopy is very low as it is a new suburb with street trees that are still growing. Compared to Maitland, Southlakes consumes significantly more energy during extreme heat events and has a higher proportion of heat-related emergency department presentations.

Local Heatwave Profile:

26 heatwave days in January 2019 – largest among the case study areas

Built Environment Heat Vulnerability Profile:

13% of the lot sizes on average are between 2,000 - 4,000 m²

1% tree canopy coverage (new suburb) – lowest among the case study areas

67% of dwellings have dark roofs – the lowest on average among the case study areas

6 minutes average time to drive to the nearest hospital – close to health facilities compared to other areas

Community Heat Vulnerability Profile:

Only **7%** are low-income households and is the least disadvantaged among the case study areas

23% of residents have one of more pre-existing health conditions – the healthiest among the case study areas

22% of residents speak a language other than English at home – the most diverse among the case study areas

20% of residents are at a vulnerable age (<4 or >65) – relatively low compared to other areas

Energy Heat Vulnerability:

Had the highest average monthly household residential energy consumption in January 2019. This was an average of **26%** higher than the Maitland precincts in the same month

Health Heat Vulnerability:

Had the highest proportion of heat-related emergency department presentations during the study period, with the highest being in March 2019.

A.4.3 The National Heat Vulnerability Observatory Index Results for Maitland and Dubbo

Existing Heat Vulnerability

Figure A-4 and Figure A-5 present the NaHVO Index results of two example SA1 areas within the Aberglasslyn and Southlakes case study precincts respectively. Namely, how their local heat vulnerability profiles influence the three heat vulnerability performance indicators. The NaHVO Index values for the thermal, energy and health vulnerability shown here represent the existing heat vulnerability values for these defined areas. These heat vulnerability index values also demonstrate the temporal and dynamic potential of the NaHVO Index by assessing the heat vulnerability for each month within the Phase 1 pilot study period. The Aberglasslyn case study example shows the NaHVO Index values for February 2020 (Figure A-4), whereas the Southlakes case study example shows the NaHVO Index values for January 2020 (Figure A-5).

As mentioned previously, these NaHVO Index values represent a relative ranking of heat vulnerability across each of the SA1 areas within the defined case study precincts for the defined project study period. These values were determined through ranking the predicted heat vulnerability key performance indicator results generated from the NaHVO Index assessment engine. The NaHVO Index values will therefore change in future phases when more cities and datasets are included within the NaHVO Index assessment engine. However, using the scope of data from this pilot application of the NaHVO Index provides insights regarding the importance of individual key influential factors in measuring heat vulnerability.

For example, the energy NaHVO Index value results showed a stronger positive correlation with the percentage of the SA1's population that have completed year 12 (or equivalent) and the monthly average number of heatwave days. This suggests that as these key influential factors increase (i.e. higher education levels and greater number of heatwaves), the average monthly residential energy consumption also increases. Conversely, the Index of Relative Socio-Economic Disadvantage (IRSD) from ABS census data and the percentage of dwellings that are semi-detached showed stronger negative correlations. It is important to recognise that these trends are only applicable to the scope of data collected in Phase 1 of the NaHVO Index and are likely to change in future phases.

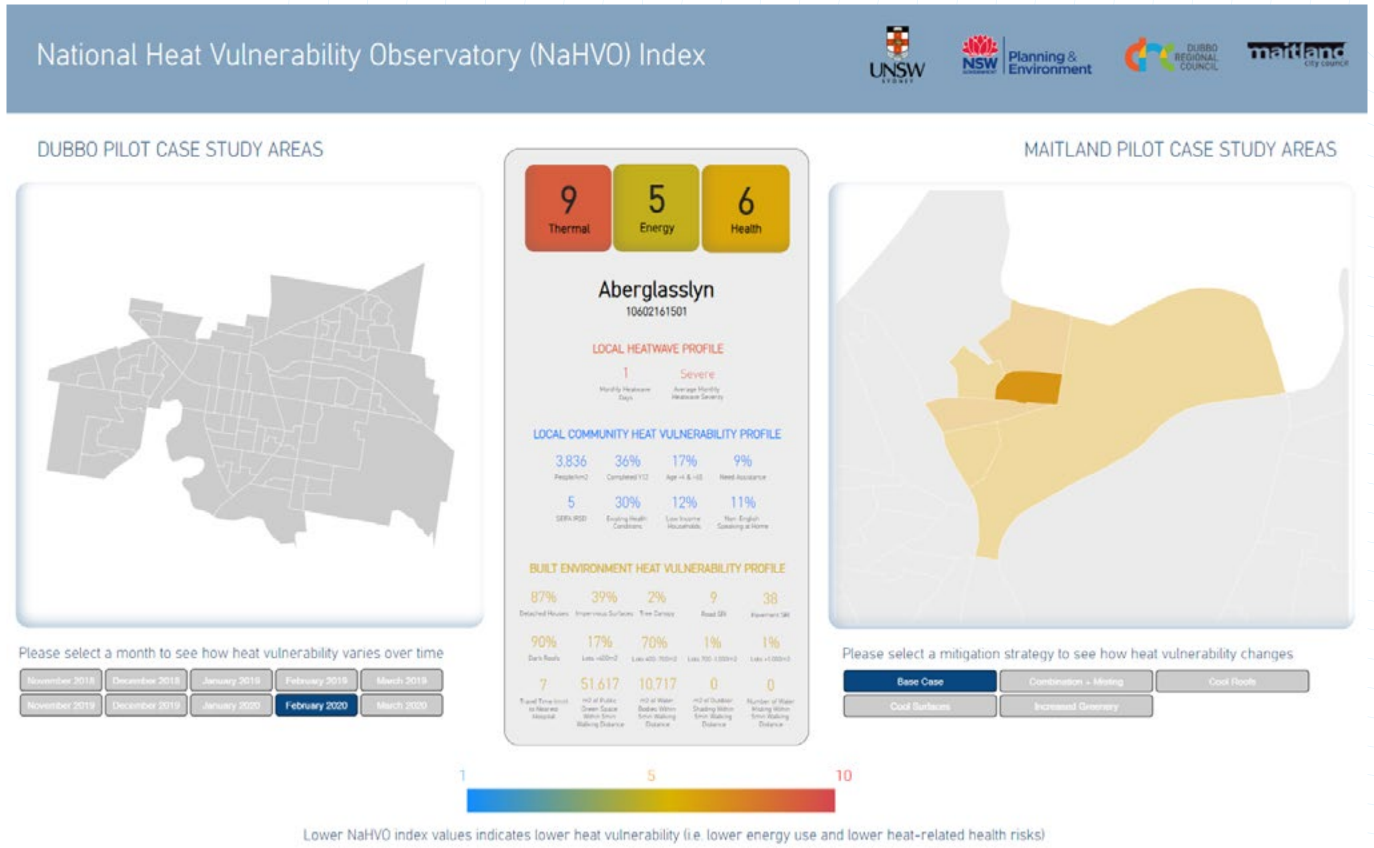


Figure A-4. NaHVO Index results for an example SA1 area within the Aberglasslyn case study precinct in February 2020.

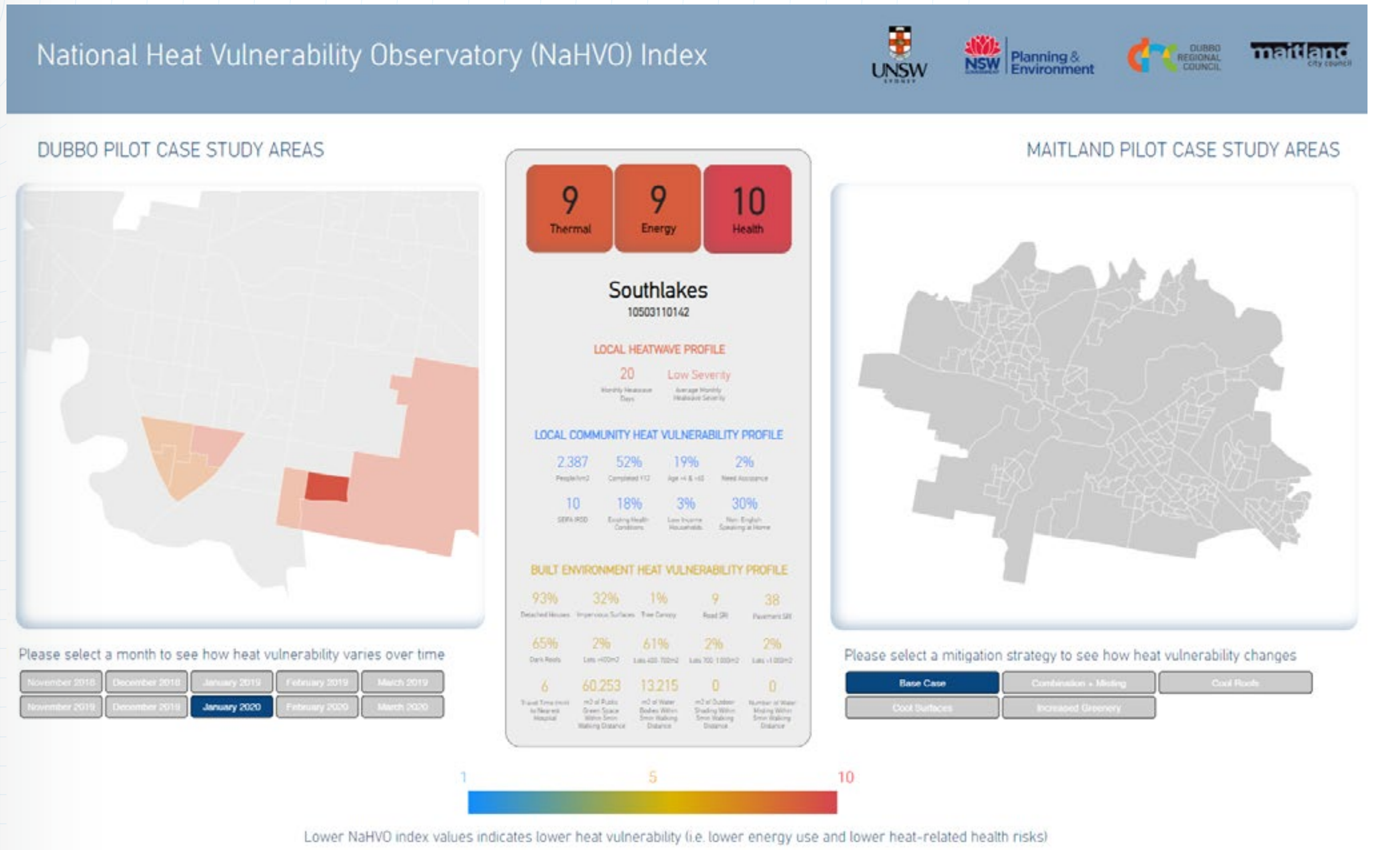


Figure A-5. NaHVO Index results for an example SA1 area within the Southlakes case study precinct in January 2020.

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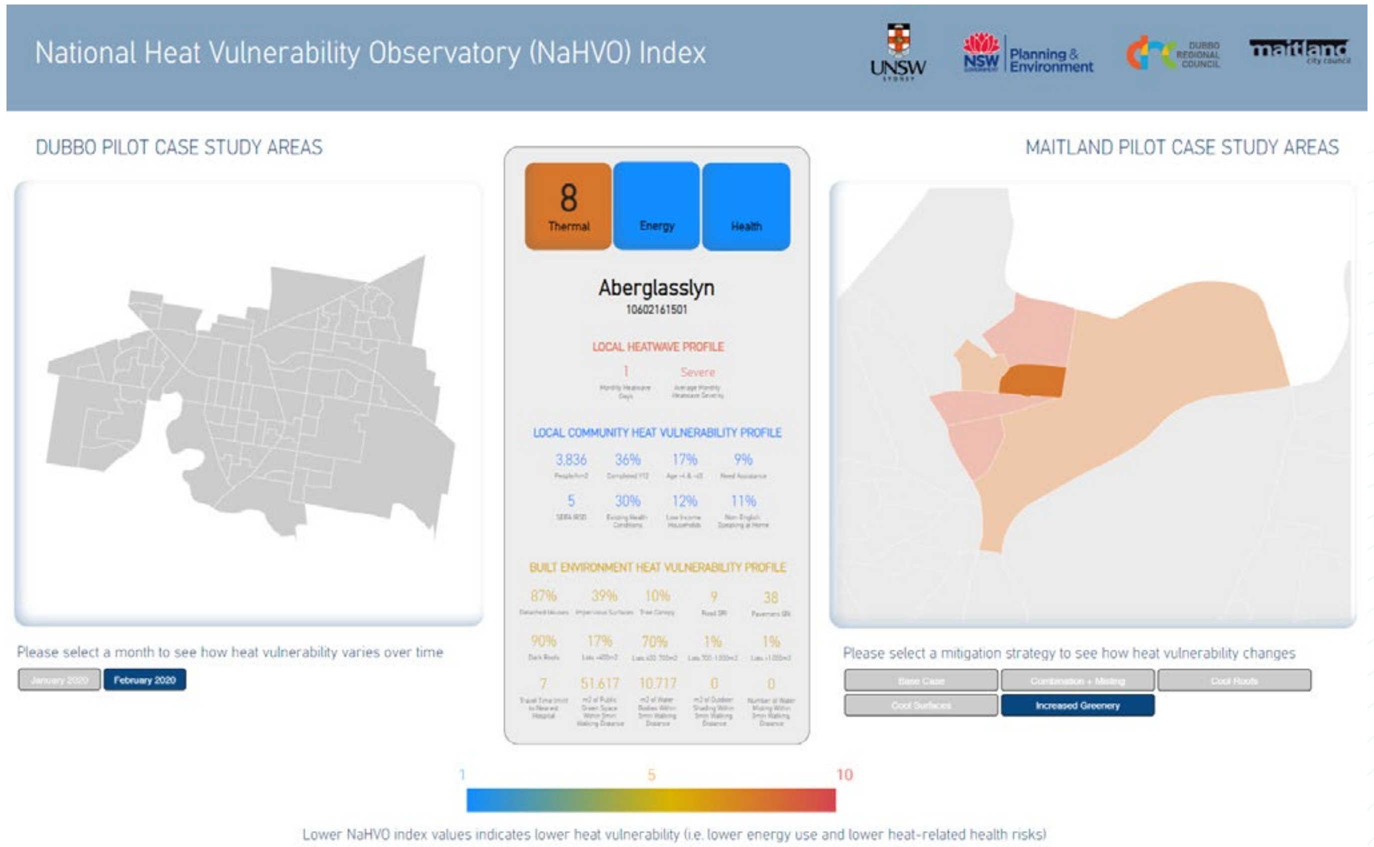

Figure A-6. Relative change in NaHVO Index values for an example SA1 area within the Aberglasslyn case study precinct in February 2020 from increasing greenery.

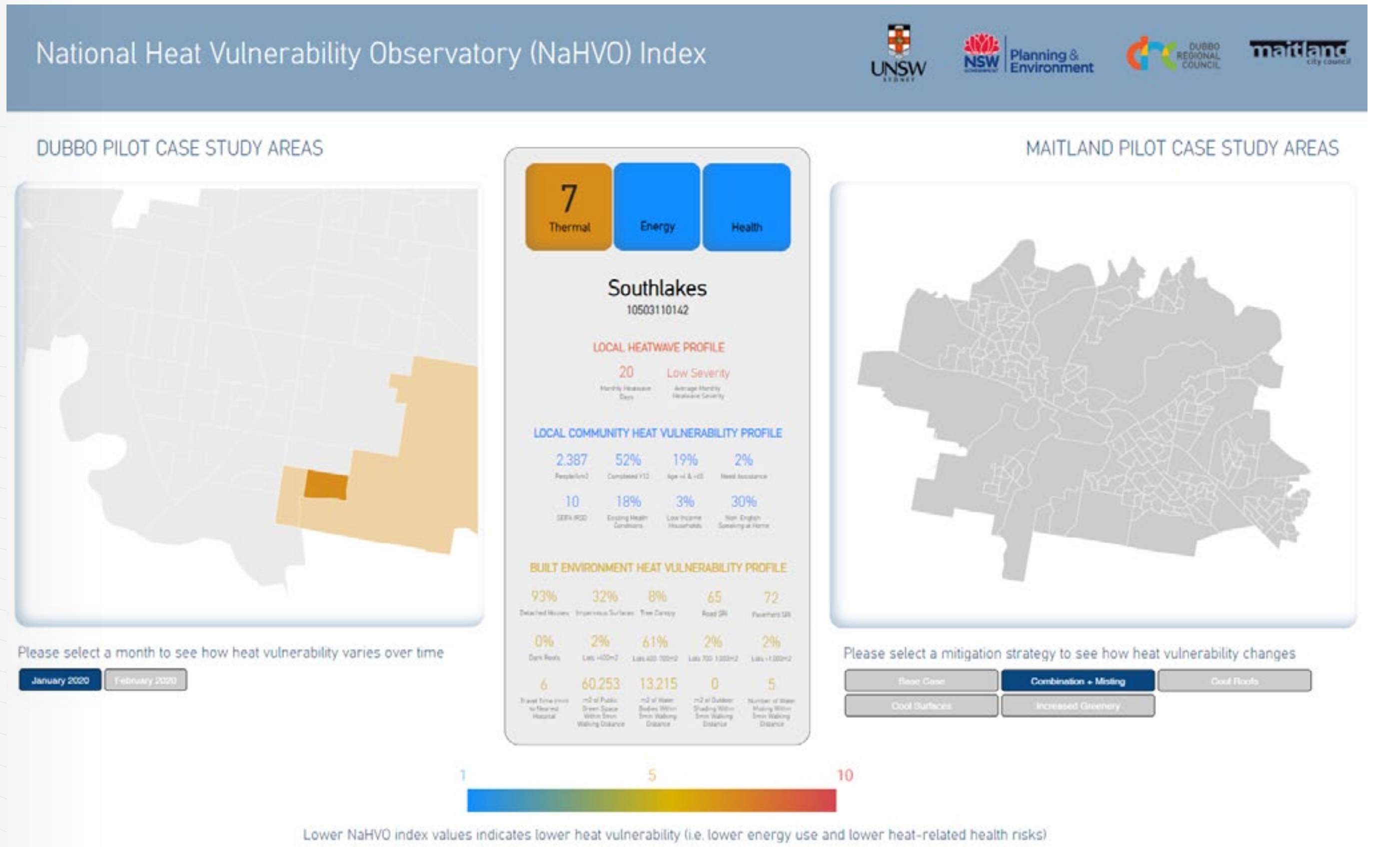

Figure A-7. Relative change in NaHVO Index values for an example SA1 area within the Southlakes case study precinct in January 2020 from a combination of mitigation strategies.

Reductions in Heat Vulnerability Through Mitigation and Adaptation Strategies

A key distinctive feature of the NaHVO Index is its ability to integrate a relative change in heat vulnerability from the application of heat mitigation and adaptation strategies. For the Phase 1 pilot of the NaHVO Index, the integration of mitigation strategies is based upon the microclimate cooling intervention scenario analysis results in the selected Maitland and Dubbo case study precincts (see Reports B and C). These mitigation strategies are linked with changes in the built environment heat vulnerability profile key influential factors. For this reason, Phase 1 of the NaHVO Index demonstrates this functionality through a relative change in the thermal heat vulnerability index value, which is based upon precinct-scale maximum potential air temperature reductions at 1pm for a selected day (see Reports B and C for detail). Future phases of the NaHVO Index will integrate additional heat mitigation and adaptation strategies and impact analysis, built upon rich evidence from more diverse range of cities in NSW and Australia.

Figure A-6 shows the relative change in thermal NaHVO Index values from increasing greenery for an example SA1 within the Aberglasslyn case study precinct. Compared to Figure A-4, which shows the existing thermal heat vulnerability index value at the same time, a relative reduction in NaHVO Index thermal values from 9 to 8 is achieved through this mitigation strategy. This mitigation strategy maximises the proportion of public and private greenery, which equated to an increase of approximately 7.7% in tree canopy for this SA1. Report B provides detailed descriptions and analysis results for all cooling intervention scenarios across the three case study precincts in Maitland.

Figure A-7 shows the relative change in thermal NaHVO Index values from a combination of mitigation strategies for an example SA1 within the Southlakes case study precinct. Compared to Figure A-5, which shows the existing thermal heat vulnerability index value at the same time, a relative reduction in NaHVO Index thermal values from 9 to 7 is achieved through this combination of mitigation strategies. This combination of mitigation strategies for this SA1 included an increase of approximately 7.5% in tree canopy as well as changing all roads, pavements and roofs to cool materials and the addition of five water misting sprays. Report C provides detailed descriptions and analysis results for all cooling intervention scenarios across the two case study precincts in Dubbo.

Report B: Maitland Case Study

Hunter River, Maitland
(© [Merrillie] / Adobe Stock).

B.1 Local Climate in Maitland

Maitland is a city in the lower Hunter Region that experiences a subtropical climate with significant rainfall in summer. The region contains large lakes that serve as an effective natural cooling system for urban heat reduction at daytime. The region has 10-20 hot days above 35 °C each year in an average. However, there has been a gradual increase in temperatures since the 1960s, and maximum temperatures are projected to increase by 2.3 °C by 2070[50].

Figure B-1 presents a satellite image of Maitland City covering an area of approximately 49 km by 37 km. Flat ground is the primary terrain feature in Maitland City, leading to an even distribution of air temperatures and winds across the city. The Urban Heat Island (UHI) intensity in the built-up area in Maitland ranges from 0.5 °C to 2.5 °C, with the UHI effect more pronounced at night in the built-up area compared to surrounding areas. UHI intensity is defined as the temperature difference between a point within the city and a reference point in the suburb. Multiple suburban reference points were selected in this project to ensure accuracy of the simulation model.

Two heatwave periods in Mainland City, occurring before the COVID-19 outbreak, were identified for analysing the maximum cooling potential of mitigation options, thereby minimising the influence of COVID-19 on health and energy in the NaHVO Index. The identified heatwave periods were (1) 22/12/2019 - 06/01/2020 and (2) 18/01/2020-02/02/2020. The gap between the two heatwave periods was noted by a continuous rainfall event.

Figure B-2 presents the daily air temperatures throughout the two heatwave periods in the built-up area. Air temperatures gradually increased, and most days were clear and sunny during the first heatwave period, while there were some cloudy days during the second heatwave period. Throughout both heatwave periods, there were 8 days with daily maximum air temperatures exceeding 40 °C, and 50% of days had a daily maximum air temperature exceeding 35 °C.

The dominant wind direction during the two heatwave periods was from the east (Figure B-3), with speeds averaging approximately 4 m/s at a height of 10 m. Figure B-4 (a) presents the wind field characteristics over the terrain in Maitland City, while Figure B-4 (b) presents the air temperature distribution at 2:00pm on a hot day (03/01/2020) during the first heatwave period. The urban heat was evenly distributed in the Maitland City area due to the primary feature of the terrain.

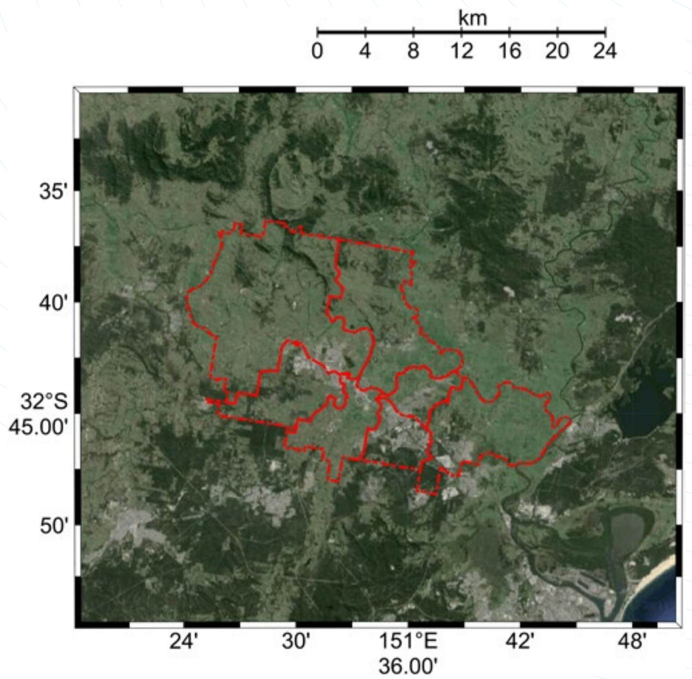

Figure B-1. A satellite image of Maitland City covering an area of approximately 49 km by 37 km.

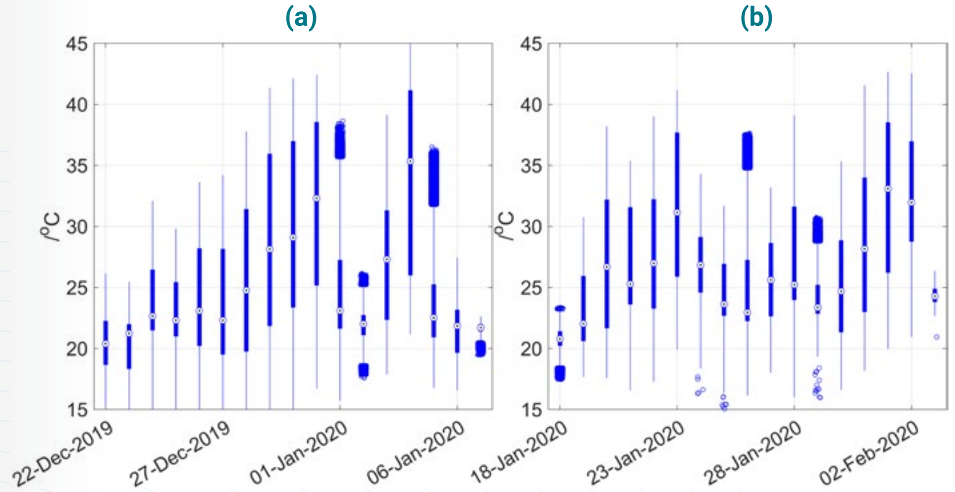

Figure B-2. (a) Daily air temperature range during the first heatwave period and (b) daily air temperature range during the second heatwave period. Where, the top of the blue box presents the 75% of air temperatures during the day, the bottom of the box presents the 25% of air temperatures during the day, and the middle point presents the median value.

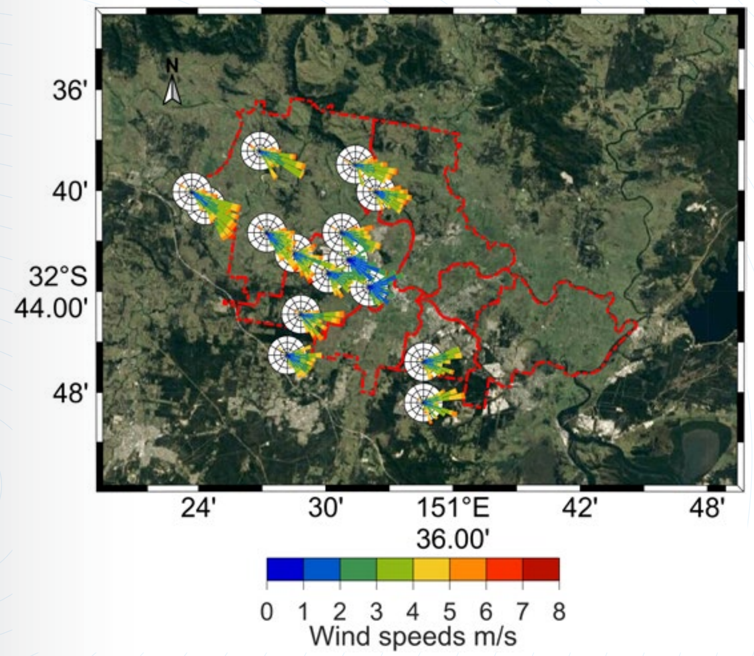

Figure B-3. Wind roses indicate the dominant wind direction during the two heatwave periods in Maitland City.

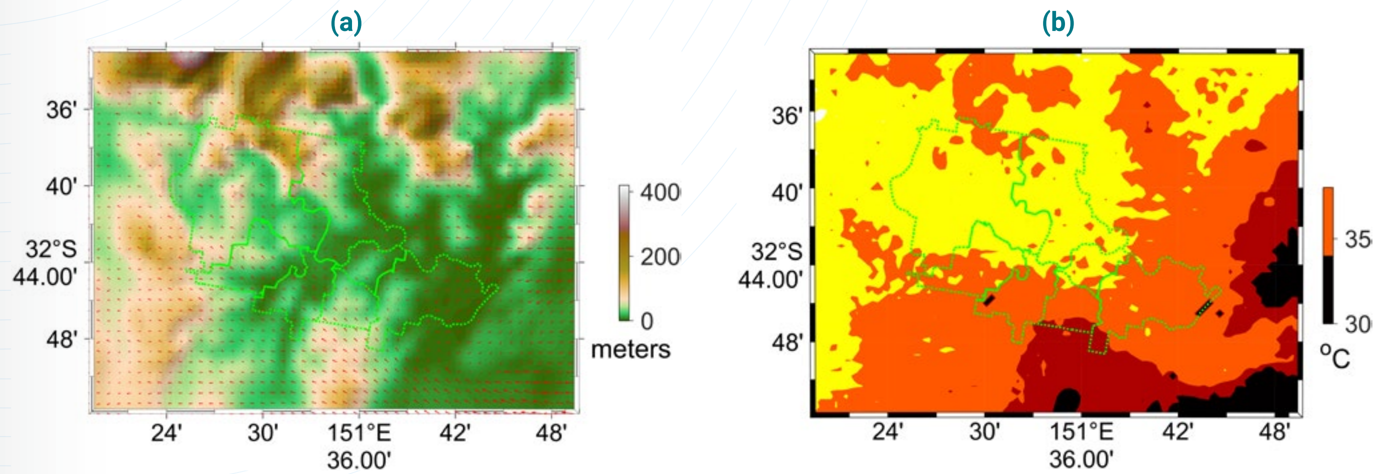

Figure B-4. (a) The wind field characteristics over the terrain in Maitland City and (b) the air temperature distribution at 2:00pm on a hot day (03/01/2020) during the first heatwave period.

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B.2 Modelling and Simulation Methods at a Mesoscale

The Weather Research and Forecasting (WRF) model was employed for the cooling potential analysis of Maitland City at a mesoscale. The WRF model is a state-of-the-art open-source mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications[51]. The adaptability of the WRF model and its integration of cutting-edge developments made it a preferred choice for the cooling potential analysis of Maitland City at a mesoscale.

Four layers of two-way nested domains were created in the WRF model for Maitland City. Outer domains had a coarser resolution while inner domains had a finer resolution. Outer domains served the role of providing dynamic boundary conditions for inner domains. The innermost domain, i.e. Domain 4 labelled d04 in Figure B-5, covers the majority of Maitland City, with a resolution 500 m in the WRF model.

The World Urban Database and Access Portal Tools (WUDAPT)[52] that covers Landsat8, along with other datasets, were employed for the landcover data in the WRF model, while the Local Climate Zone (LCZ) schema[53] is utilised for classifying the surface structure (e.g. building and tree height, and their densities) and surface cover (e.g. pervious and impervious surface covers). Anthropogenic heat was included in the WRF model through a dynamic parameterisation schema. The actual value of anthropogenic heat at each grid point in the WRF model changes based on the real-time cooling load within buildings over time. Figure B-6 presents the land use and LCZ in Maitland City, and Figure B-7 presents the peak anthropogenic heat from HVAC over different LCZs in Maitland City.

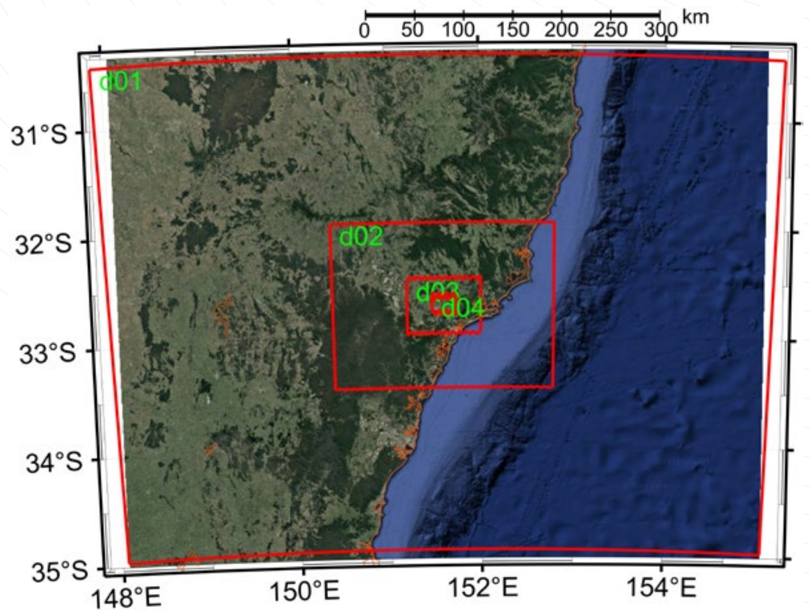

Figure B-5. Domains setting in WRF model, where d04 denotes Domain 4 covering a 48.5 km x 36.5 km area encompassing the majority of Maitland City. Domain 4 (d04) has a resolution 500 m in the WRF model.

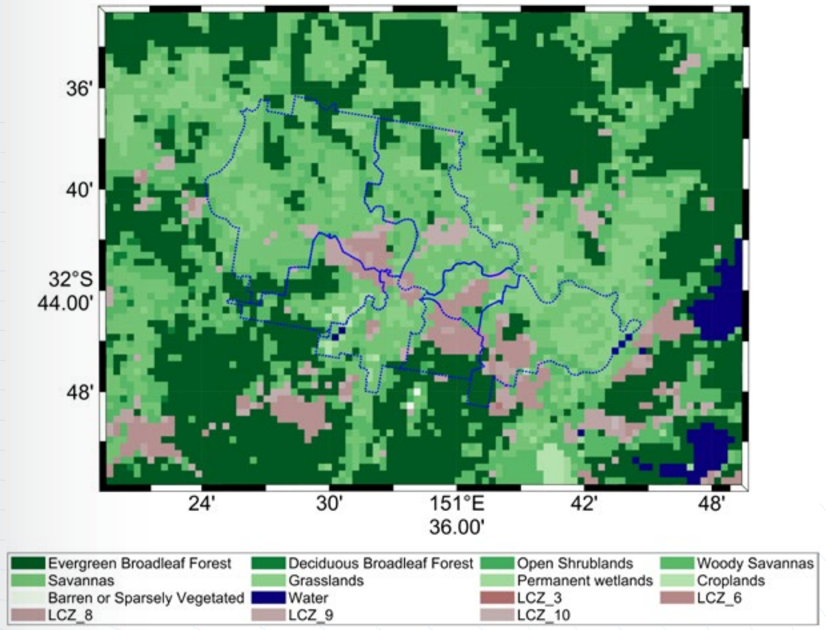

Figure B-6. The land use and LCZ in Maitland City in the WRF model.

The validation of the WRF model was conducted by comparing the simulation results with weather station data to ensure feasibility and accuracy. All available weather stations within Maitland from the Bureau of Meteorology (BOM) were used for validation, including Cessnock Airport (-32.7914, 151.3369), Maitland Airport (-32.7023, 151.4881), and Paterson weather station (-32.6296,151.5919). Table B-1 outlines the comparison results between the weather station and simulation data of air temperature at 2 m, relative humidity at 2 m, and wind speed at 10 m during the two heatwave simulation periods.

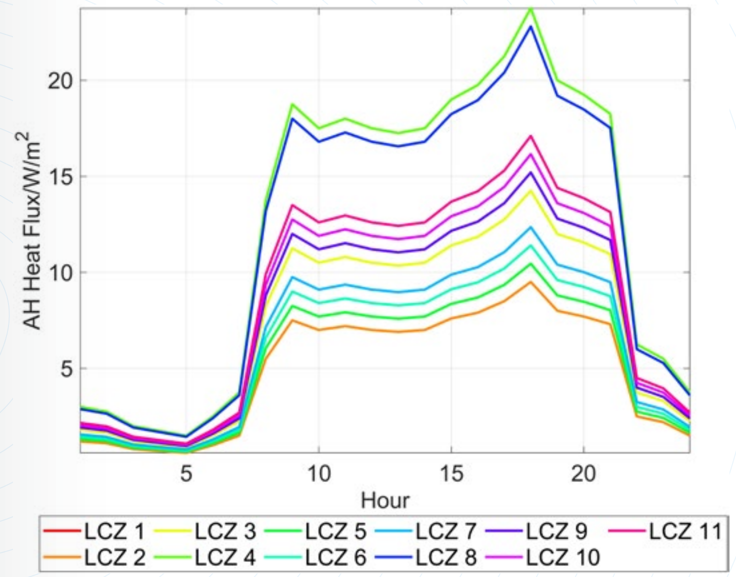

Figure B-7. The peak anthropogenic heat from HVAC over different LCZs in Maitland City.

Table B-1. The comparison results between the weather station and simulation data of air temperature at 2 m, relative humidity at 2 m, and wind speed at 10 m during the two heatwave simulation periods. Where, ME denotes mean bias, FB denotes fractional bias, R denotes correlation coefficient, NMSE denotes normalised mean square error, and FAC2 denotes the fraction of simulation values within a fraction of two of weather station data.

Statistical Parameter	December 22nd, 2019, to January 8th, 2020			January 18th, 2020, to February 3rd, 2020		
	Temperature/ °C	Relative humidity/%	Wind speed/ m/s	Temperature/ °C	Relative humidity/%	Wind speed/ m/s
MB	0.352	3.225	-0.850	0.171	-1.075	-0.649
FB	0.016	0.054	-0.212	0.008	-0.020	-0.080
R	0.970	0.952	0.827	0.951	0.873	0.735
NMSE	0.000	0.000	0.001	0.000	0.000	0.001
FAC2	1.000	0.995	0.859	1.000	0.990	0.706

B.3 Urban Heat Mitigation Strategies at a Mesoscale

Key mitigation strategies were applied to Maitland City to understand the maximum cooling potential at the mesoscale. These mitigation strategies included cool materials with increased albedo for urban hard surfaces such as roads and roofs, increased greenery with broadleaf trees, increased greenery with water irrigation, and a combination of all these mitigation options (Table B-2).

Cool Materials

Cool materials were applied to urban hard surfaces including roads, impervious pavements, and roofs to reduce the shortwave radiation absorbed by the city, thereby achieving a cooling effect through a reduction in surface sensible heat. This mitigation strategy included increasing the albedo value from 0.3 to 0.8 for roofs and from 0.15 to 0.5 for roads and impervious pavements. As a result, the overall average albedo of the urban grid in the model was increased from the 0.25 to 0.35 for the study area (Figure B-8).

Greenery

Urban greenery comprises a mix of grass, shrubs and trees. This mitigation strategy focused on tree planting, which included replacing existing trees with broadleaf trees, and increasing trees coverage in the built area to 40% to understand the maximum cooling potential by enhancing urban greenery. This increase covers the transitional zones between dispersed built-up areas in Maitland. Figure B-9 (a) and (b) show the existing and increased urban greenery coverage respectively in Maitland, while detailed parameters for urban greenery are provided in Appendix 1.

Table B-2. List of urban heat mitigation strategies at the mesoscale.

ID	MITIGATION STRATEGY NAME	MITIGATION STRATEGY DESCRIPTION
S0	Base case	It refers to the existing site.
S1	Cool Materials	High albedo materials were applied to urban hard surfaces, including roads, impervious pavements, and roofs.
S2	Greenery	Urban greenery was increased and replaced with broadleaf trees, and the suburban area was also planted with broadleaf trees.
S3	Greenery with Irrigation	Urban greenery was increased and replaced with broadleaf trees, and the suburban are was also planted with broadleaf trees. Additionally, dynamic water irrigation was applied to all green infrastructure to maintain soil moisture at optimal levels for transpiration.
S4	Combination	A combination of all the above mitigation strategies (S1, S2 and S3).

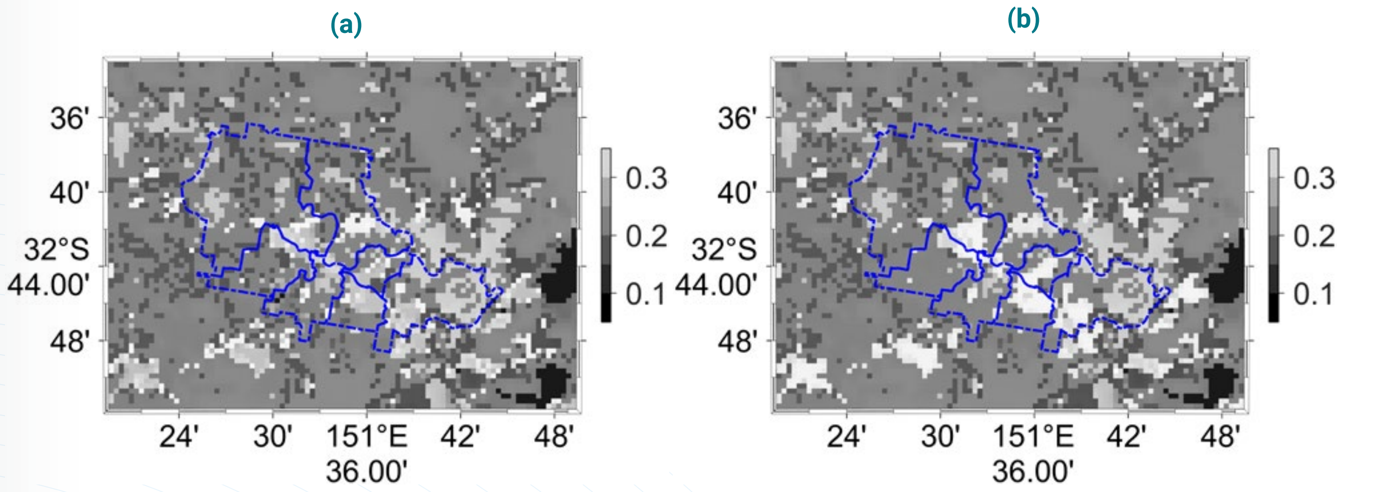

Figure B-8. The albedo values of urban hard surfaces: (a) base case and (b) cool materials applied to roads, impervious pavements, and roofs in Maitland City.

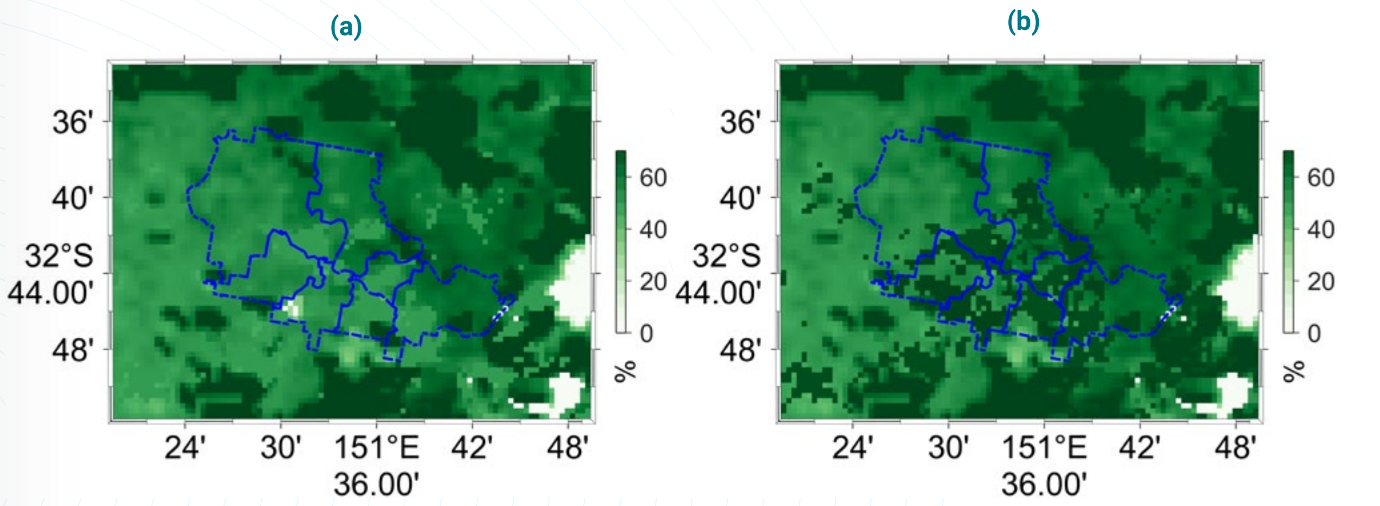

Figure B-9. The urban greenery fraction: (a) base case and (b) increased urban greenery in Maitland City.

Greenery with Water Irrigation

Dynamic water irrigation was applied to urban greenery, considering the significant impact of water transpiration on urban greenery. This mitigation strategy monitors soil moisture levels and provides timely water irrigation to maintain optimal soil moisture for maximising transpiration. It increased the average soil moisture during the two heatwave periods by 1 m^3/m^3 on the top layer of the soil (0-10 cm) for the urban greenery area, including increased tree coverage. Figure B-10 (a) and (b) show the average soil moisture of the existing urban greenery coverage and increased urban greenery coverage respectively.

Combination of Mitigation Options

A combination of all the above mitigation strategies was applied to Maitland City to understand the maximum cooling potential across the entire area. This included the application of cool materials to roads, impervious pavements, and roofs, as well as increasing urban greenery with water irrigation.

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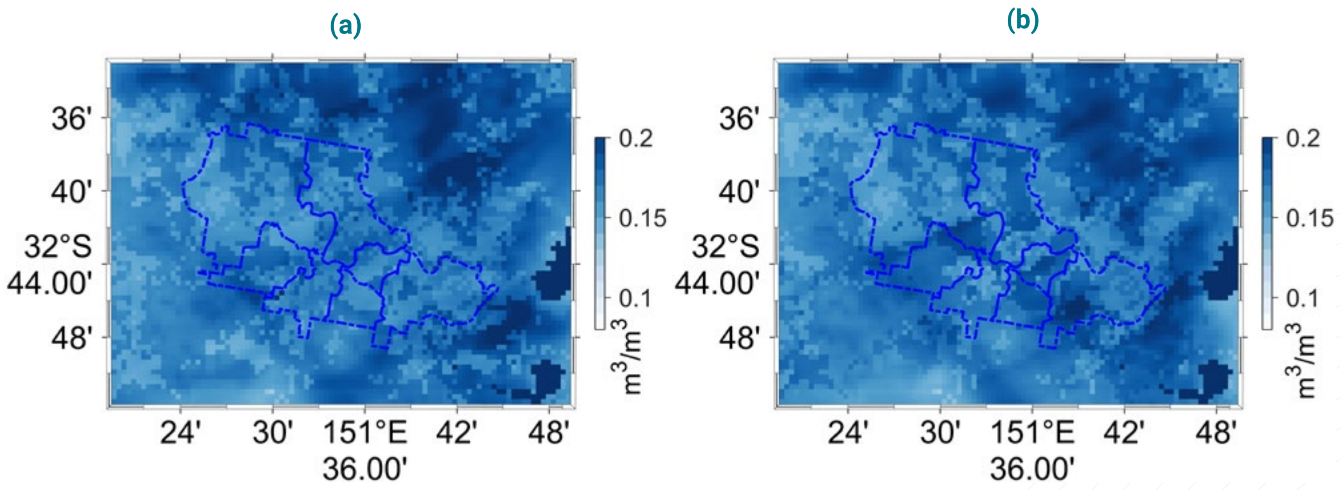


Figure B-10. The average soil moisture on the top layer of the soil (0-10 cm): (a) base case and (b) increased urban greenery coverage.City.

B.4 Cooling Potential Analysis for Maitland at a Mesoscale

B.4.1 Cooling Potential by Mitigation Strategies at a Mesoscale

The maximum daily cooling potential of the different mitigation strategies (as described in Section B.3) is shown in Figure B-11. The application of cool materials contributed to significant air temperature reduction, especially during the daytime, while increasing urban greenery with water irrigation contributed to air temperature reduction during both daytime and nighttime. Urban greenery with water irrigation had higher cooling benefits compared to urban greenery without water irrigation. The combination of all mitigation options achieved the highest cooling effect, with air temperature reduction up to 1.6 °C. These results were for the built-up area within Maitland City rather than the entire area of Maitland City. The built-up area is more dispersed in Maitland City compared to the Dubbo Region, making it challenging to achieve a larger cooling effect across the entire city. As a result, the maximum cooling effect in Maitland City was slightly lower than in the Dubbo Region.

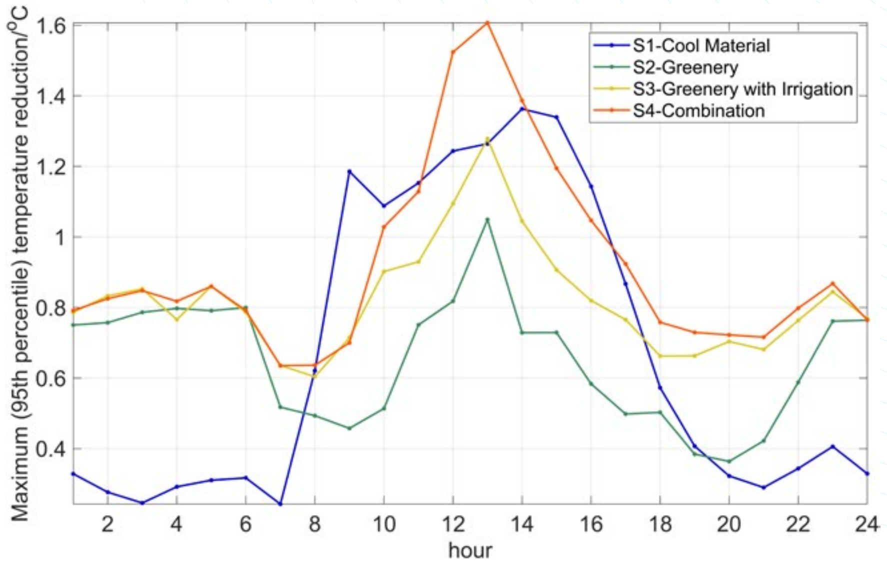


Figure B-11. The maximum daily cooling potential of the different mitigation strategies (as described in Section B.3), which refers to the 95th percentile of maximum daily air temperature reductions during the heatwave periods.

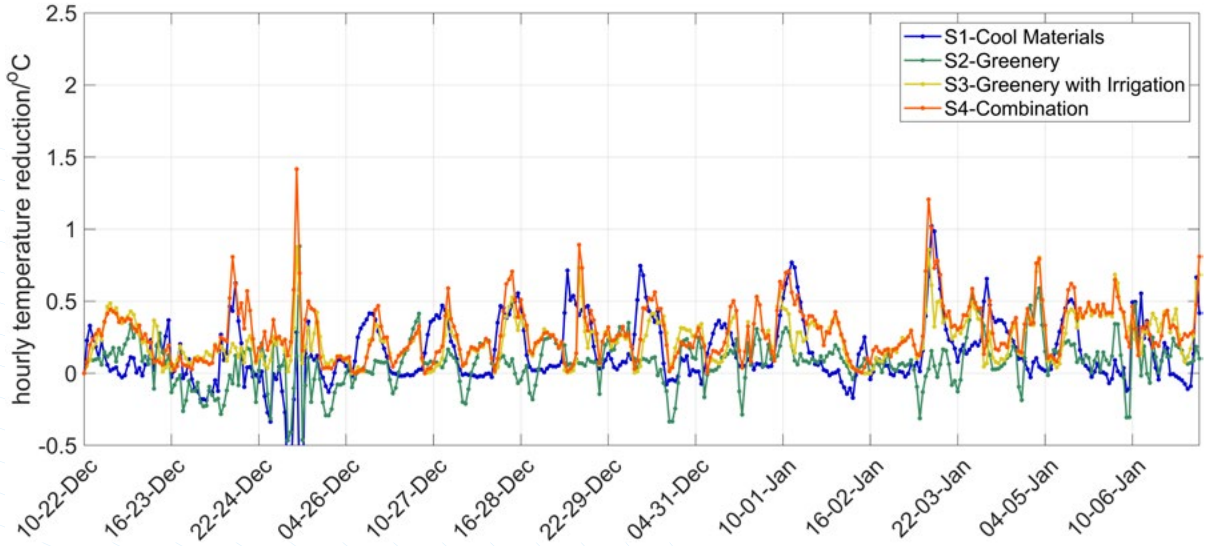


Figure B-12. The maximum air temperature reduction hourly during the first heatwave period.

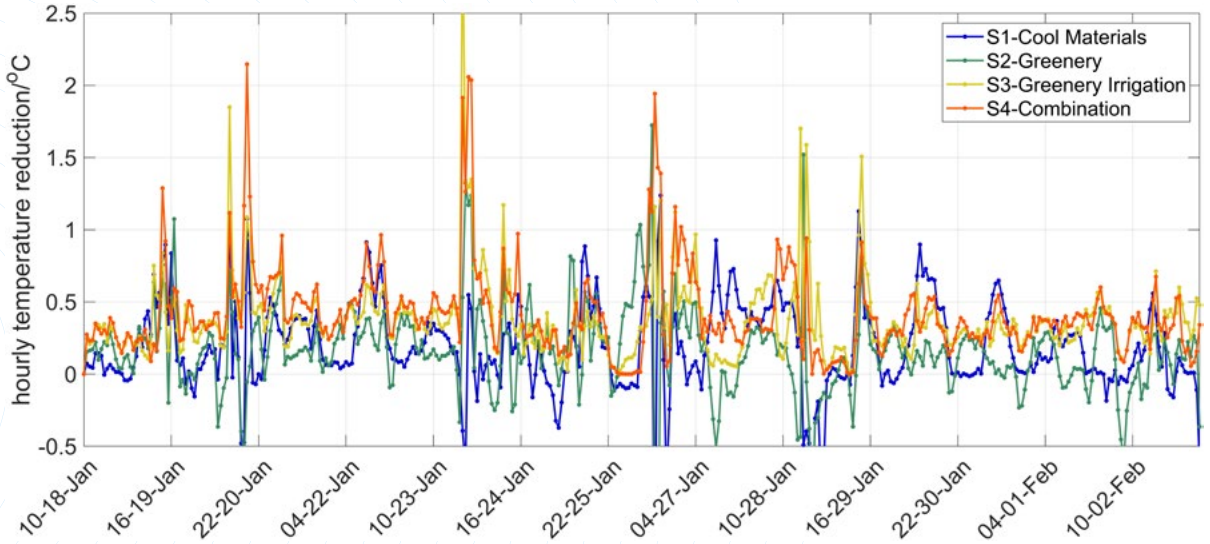


Figure B-13. The maximum air temperature reduction hourly during the second heatwave period.

Figure B-12 and Figure B-13 show the maximum cooling effect hourly during the first and second heatwave periods respectively. The cooling effect from the application of cool materials remained stable and consistent throughout the first heatwave period and did not show a significant advantage compared to increasing urban greenery with water irrigation (Figure B-12). The cooling effect from increasing urban greenery with water irrigation showed larger cooling amplitudes during the second heatwave period (Figure B-13). This demonstrates that the cooling effect of increasing urban greenery with water irrigation highly depends on weather conditions, being more sensitive to daily weather variations, which resulted in significant differences between different days. It was observed that urban greenery without water irrigation could result in an evening warming trend. The daily cooling peaks from urban greenery with water irrigation occurred slightly later, typically around 1-2 hours later. This phenomenon could be attributed to the diurnal pattern of evapotranspiration, which is influenced by daily weather cycles.

B.4.2 Water Consumption Resulting from Water Irrigation for Urban Greenery

Daily water consumption from urban greenery with irrigation was predicted based on the cumulative changes in accumulated evapotranspiration. The average daily water irrigation volume for urban greenery in the built-up area ranged from 1.9 mm to 8 mm over the two heatwave periods (Figure B-14). Specially, the estimated total daily water consumption ranged from 440 m³/km² to 1180 m³/km², depending on weather conditions.

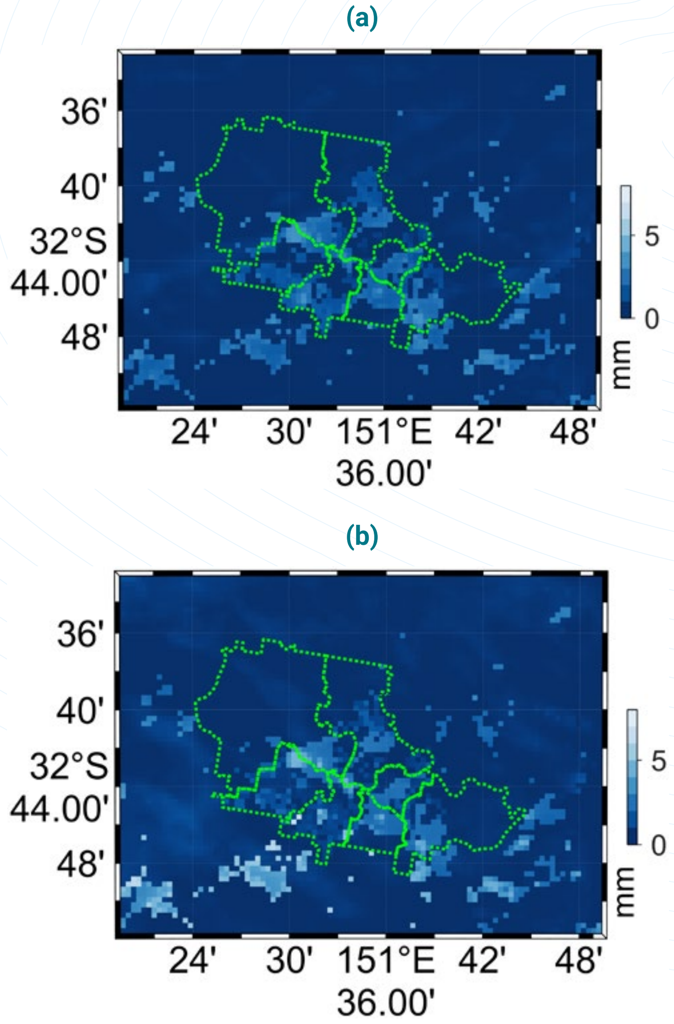


Figure B-14. The estimated average daily water irrigation volume for urban greenery in the built-up area during: (a) the first heave period and (b) the second heatwave period.

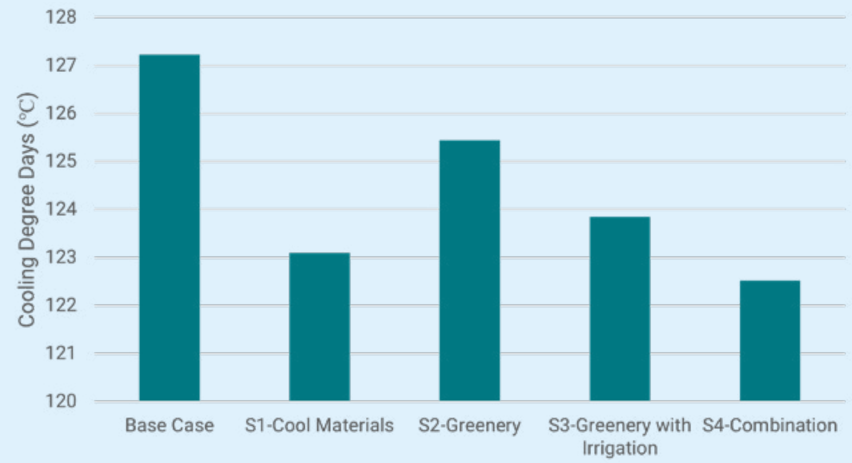


Figure B-15. The estimated reduction in CDD in Maitland resulting from the implementation of the mitigation strategies at the mesoscale.

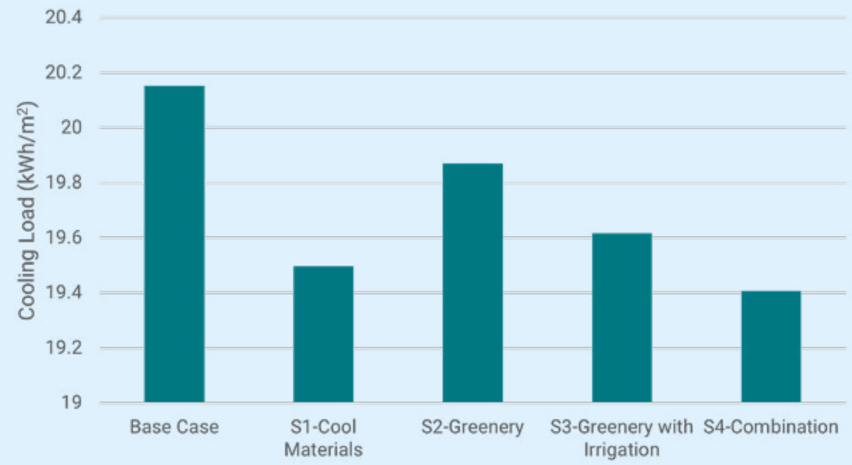


Figure B-16. The estimated decrease in cooling loads for a representative house in Maitland resulting from the implementation of the mitigation strategies at the mesoscale.

B.4.3 Reduction in Cooling Degree Days and Cooling Loads

The Cooling Degree Days (CDD) indicator measures the accumulation of degrees and duration of time where the outdoor average air temperature exceeds a defined base air temperature, indicating the need for cooling. This indicator is often used for assessing the severity of urban heat and forecasting cooling loads in buildings. For this project, a base temperature of 23 °C was defined.

The mitigation strategies at the mesoscale, described in Section B.3, demonstrated the potential to achieve significant reductions in Cooling Degree Days (CDD) in Maitland, as shown in Figure B-15. This reduction in CDD corresponds to energy savings in cooling loads for buildings. Figure B-16 estimates the decrease in cooling loads for a representative house in Maitland resulting from the implementation of these mitigation strategies.

B.5 Cooling Potential for Maitland at a Microscale

B.5.1 Modelling and Simulation Methods at a Microscale

This project also conducted the cooling potential analysis at a microscale for case study precincts in Maitland, specifically Aberglasslyn, Chisholm and Gillieston Heights. The computational Fluid Dynamic (CFD) based model, ENVI-met, was employed for the microscale cooling potential analysis, while DesignBuilder software was used for the energy analysis of buildings. Additionally, the validation of the CFD model was conducted by comparing simulation results with field measurement results.

Key Parameters

February 1, 2020 during the second heatwave period (refer to Section B.1), was selected for the CFD model at a microscale. It was a hot, sunny day with a maximum temperature of 41.5 °C. The daily average wind speed was 3.8 m/s, predominantly from the southeast. The simulation time was set from 7:00 to 24:00 to analyse the cooling potential, covering both daytime and nighttime. Heatmaps were generated for 14:00 to show air and surface temperature distributions across the case study precincts in Maitland. Air temperatures at pedestrian level (1.5 m) and surface temperatures on the ground were used for a comparative analysis of the cooling potential.

Table B-3 lists parameters for urban surfaces and building materials, while Table B-4 provides properties of trees in the model. All these parameters were validated prior to the simulations. Cool materials used for cool roofs, cool pavements, and cool roads are the existing cool materials commonly used, rather than advanced super cool materials currently under development.

Table B-3. Parameters for urban surfaces and building materials in the model.

Urban Surfaces or Building Materials	Albedo	Emissivity
Light-coloured corrugated metal roof for residential buildings	0.60	0.60
Dark-coloured corrugated metal roof for residential buildings	0.30	0.60
Brick walls for residential buildings	0.30	0.93
Concrete roofs and walls for commercial buildings	0.20	0.94
Cool roofs	0.80	0.85
Soil	0.15	0.90
Concrete pavement	0.20	0.90
Asphalt roads	0.08	0.90
Cool pavement	0.60	0.90
Cool asphalt roads	0.55	0.90
Grass	0.20	0.97
Trees	0.18	0.96

Table B-4. Properties of trees in the model.

Sizes	Tree Height (m)	Canopy Width (m)
Small	8.14	6.19 x 6.12
Medium	13.20	9.31 x 9.46
Large	21.26	11.65 x 11.90

Model Validation

An on-site measurement was conducted for model validation. It compared air temperatures, relative humidity, wind speeds and directions, and solar radiation from simulations to the measurement results. Model validation results showed that the simulation results were close to the measurement results (Figure B-17).

Sensor Data

Sensors for monitoring air temperatures and humidities were installed at the case study precincts in Maitland City. These sensors were used for both model validation and ongoing monitoring of outdoor thermal environments, as well as future changes in outdoor thermal comfort resulting from the implementation of mitigation strategies. Figure B-18 presents sensor data of air temperatures collected on 25 January 2024 from the case study precincts: Aberglasslyn, Chisholm and Gillieston Heights.

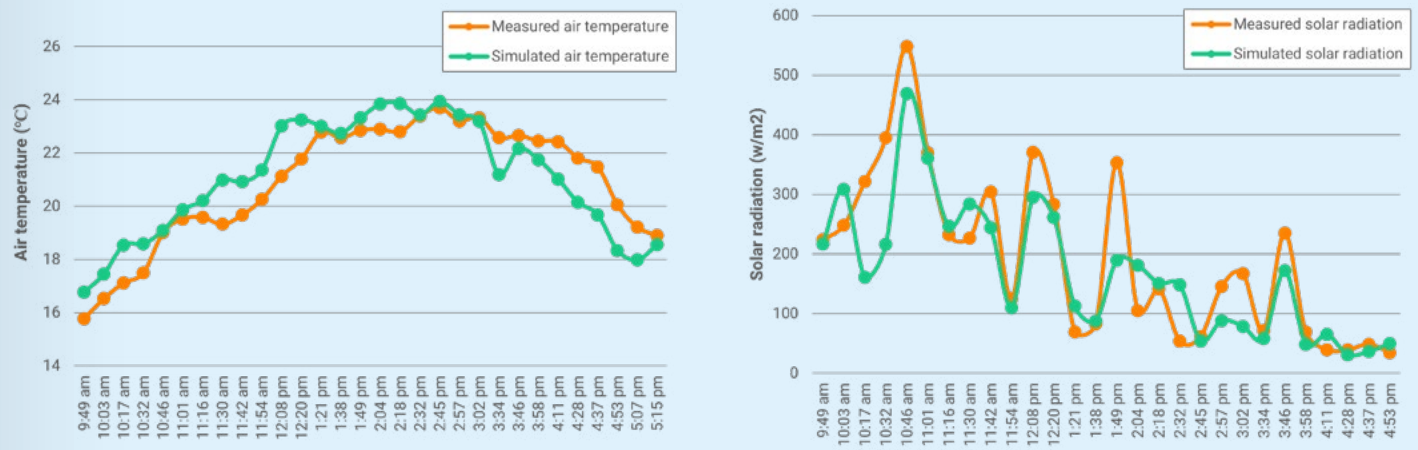


Figure B-17. Model validation results show that the simulation results are close to the measurement results.

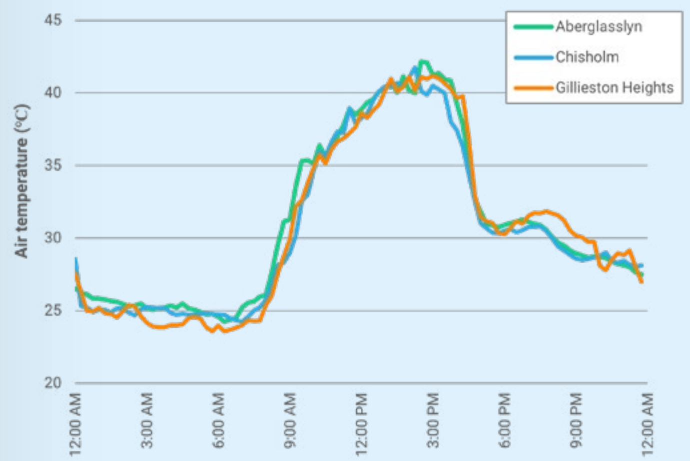


Figure B-18. Sensor data of air temperatures collected on 25 January from the case study precincts: Aberglasslyn, Chisholm, and Gillieston Heights.

B.5.2 Urban Heat Mitigation Strategies at a Microscale

In alignment with the urban heat mitigations strategies at a mesoscale (refer to Section B.3), mitigation strategies for the case study precincts in Maitland were co-designed by the project team and the Maitland City Council. These mitigation strategies were developed based on the specific local built environment characteristics and heat vulnerability challenges identified to understand the maximum cooling potential. For instance, dark roofs are dominant in detached houses, and large outdoor parking areas have low tree canopy coverage, leading to high surface temperatures, etc. (refer to detailed analyses in Section B 5.3).

Table B-5 lists the mitigations strategies applied to the three case study precincts in Maitland: Abglasslyn, Chisholm and Gillieston Heights. These mitigation strategies encompassed both public and private realms. In-depth analyses were provided for Aberglasslyn, including energy savings from cool roofs and the maximum cooling potential of individual and combined mitigation strategies for outdoor thermal environments.

Table B-5. The mitigations strategies applied to the case study precincts in Maitland.

CASE STUDY PRECINCTS	INDIVIDUAL AND COMBINED MITIGATION STRATEGIES
Aberglasslyn	Base case
	Increased public and private greenery
	Cool materials for all roads, footpaths and private hard surfaces
	Cool roofs for all buildings
	Combination of increased greenery, cool pavements, and cool roofs applied with additional water misting for hotspots and outdoor shading for public open spaces
	Cool roof energy savings
Chisholm	Base case
	Combination of increased greenery, cool pavements, and cool roofs applied with additional water misting for hotspots and outdoor shading for public open spaces
Gillieston Heights	Base case
	Combination of increased greenery, cool pavements, and cool roofs applied with additional water misting for hotspots and outdoor shading for public open spaces

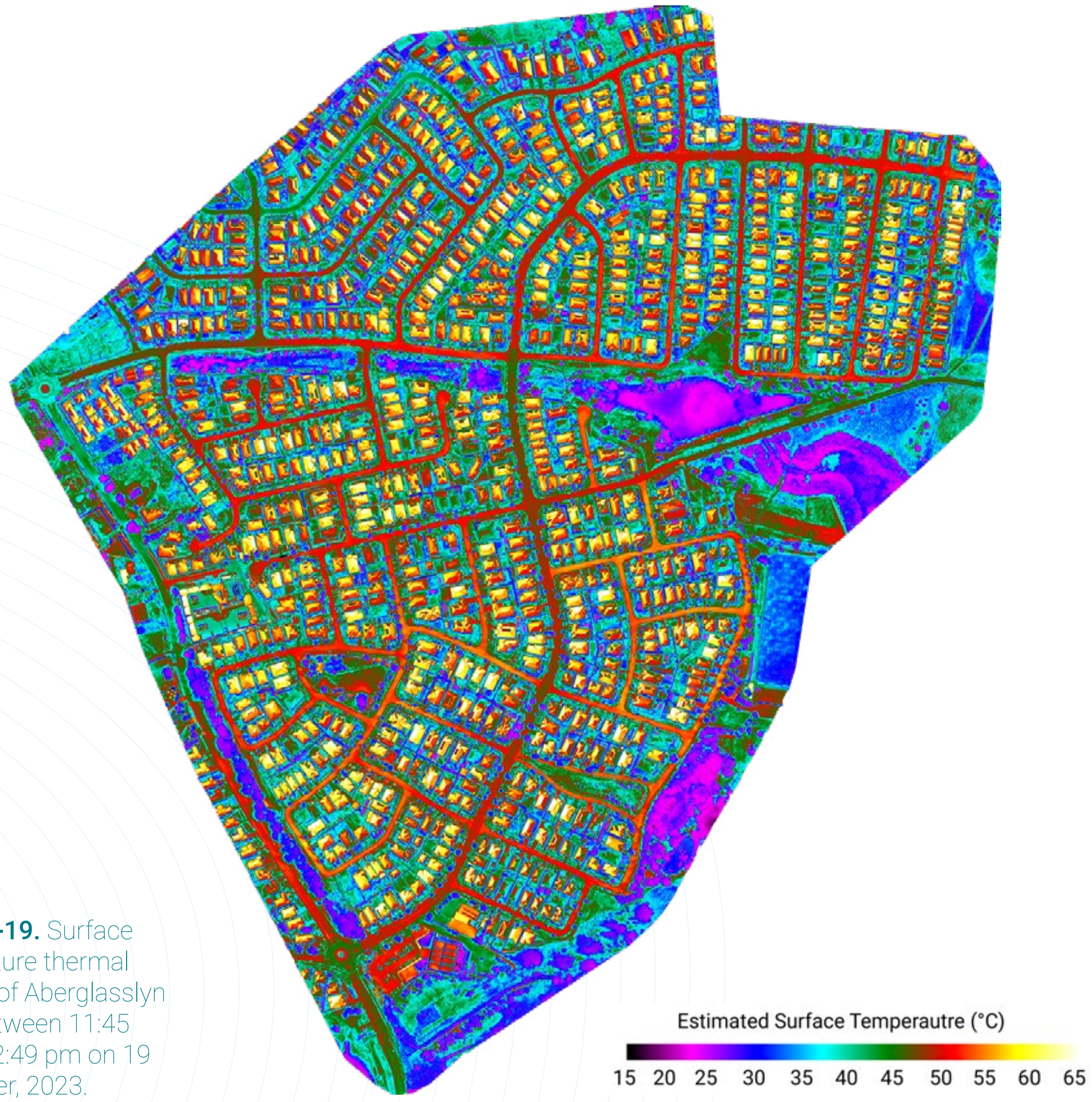


Figure B-19. Surface temperature thermal imagery of Aberglasslyn taken between 11:45 am and 2:49 pm on 19 November, 2023.

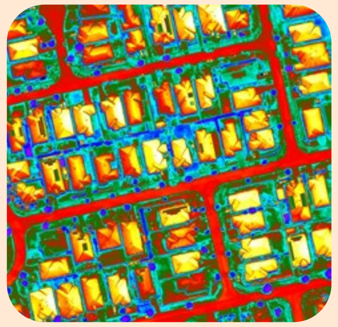
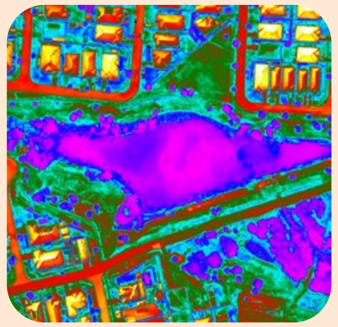
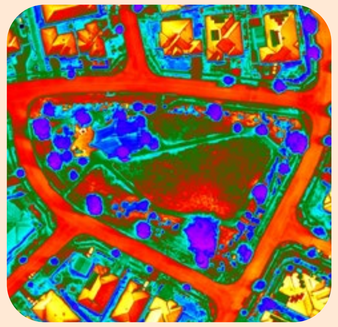
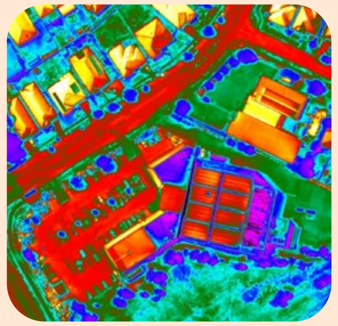
B.5.3 Cooling Potential of Mitigation Strategies in Aberglasslyn

Heat Vulnerability Challenges and Built Environment Characteristics of Aberglasslyn

Maitland City Council identified the suburb of Aberglasslyn as one of the key vulnerable areas to heat based on a previous study[54]. It comprises detached one and two-storey houses on relatively small lots, which leaves few opportunities for private green space and tree canopy coverage. It also has relatively low tree canopy coverage along its narrow streets, resulting in high surface temperatures from unshaded roads (shown in red in Figure B-19). Compared to the other case study precincts in the Phase 1 pilot of the NaHVO, Aberglasslyn has the highest proportion of dwellings with dark roofs, which leads to high roof surface temperatures for most dwellings across the precinct (shown in yellow and white in Figure B-19). Aberglasslyn also had the highest daily temperature within the Phase 1 study period of 41.5 °C according to the mesoscale simulation results. Based on the NaHVO Index results, Aberglasslyn presented predominantly moderate thermal, energy and health heat vulnerability index values throughout the Phase 1 study period. The detailed built environment characteristics and heat vulnerability challenges for Aberglasslyn are provided in Table B-6.

Aberglasslyn represents the typical residential development typology for future growth in Maitland and as such, it was the major focus of the heat mitigation strategies for Maitland. This section presents the cooling potential results for the six heat mitigation scenarios for Aberglasslyn outlined in Table B-5. These results are presented as reductions in air and surface temperature for a representative hot summer's day (including the evening) during the NaHVO's Phase 1 study period (see B.5.1), as compared to the existing conditions (base case) of Aberglasslyn.

Table B-6. Built environment characteristics and heat vulnerability challenges in Aberglasslyn.

THERMAL IMAGERY	AERIAL IMAGERY	STREETSCAPE	BUILT ENVIRONMENT CHARACTERISTICS	HEAT VULNERABILITY CHALLENGES
			» Low-rise detached residential buildings with a compact layout. » Small to moderate areas of pervious and impervious private open space with limited trees. » Narrow roads with low street tree canopy coverage. » High proportion of dark-coloured roofs.	» Exposed private open space due to limited private tree canopy. » Exposed hard surfaces with high surface temperatures along streets from limited tree canopy. » Narrow roads limit the opportunities for raingardens and outdoor shading. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Small water body accessible to the public with narrow footpaths and low to moderate tree canopy coverage surrounding it.	» Small water bodies can only provide a limited cooling effect for its immediate surroundings.
			» Public green open space with moderate tree canopy coverage and outdoor shading for play equipment.	» Areas of unirrigated and unshaded grass have higher surface temperatures.
			» Low-rise commercial buildings (supermarket and childcare facility). » Large, exposed light and dark roof surfaces with significant number of solar panels. » Large outdoor carparking areas with low tree canopy coverage.	» High roof surface temperatures for darker roof materials, especially underneath solar panels. » Exposed hard surfaces with high surface temperatures in car parking areas from limited tree canopy or outdoor shading. » High surface temperatures in unshaded hard surfaced areas of the childcare facility.

- Base Case -

Figure B-20 shows the modelled existing conditions of Aberglasslyn including 3D building objects and trees, road and footpath networks, and water bodies. This was generated from a wide range of data sources from Maitland City Council, open-source datasets, and satellite imagery (see Report D for more detail). This model of Aberglasslyn was used to simulate a base case scenario, which formed the basis to compare the defined cooling intervention scenarios against. As mentioned in Section B.5.1, this base case model was validated with on-site measurements for air temperature, relative humidity, wind speed and direction, and solar radiation to ensure the simulated results were as close as possible to reality.

Figure B-21 presents the air temperature distribution of the simulated base case at 2pm for the Aberglasslyn case study precinct. This shows that the air temperature were generally higher along the roads that have minor tree canopy coverage. However, the small water body to the east of the precinct's boundary and its public green spaces provided effective localised cooling impacts with air temperatures of approximately 2 to 4 °C less than other areas of the precinct.

View of Aberglasslyn via drone aerial photography (UNSW High Performance Architecture).

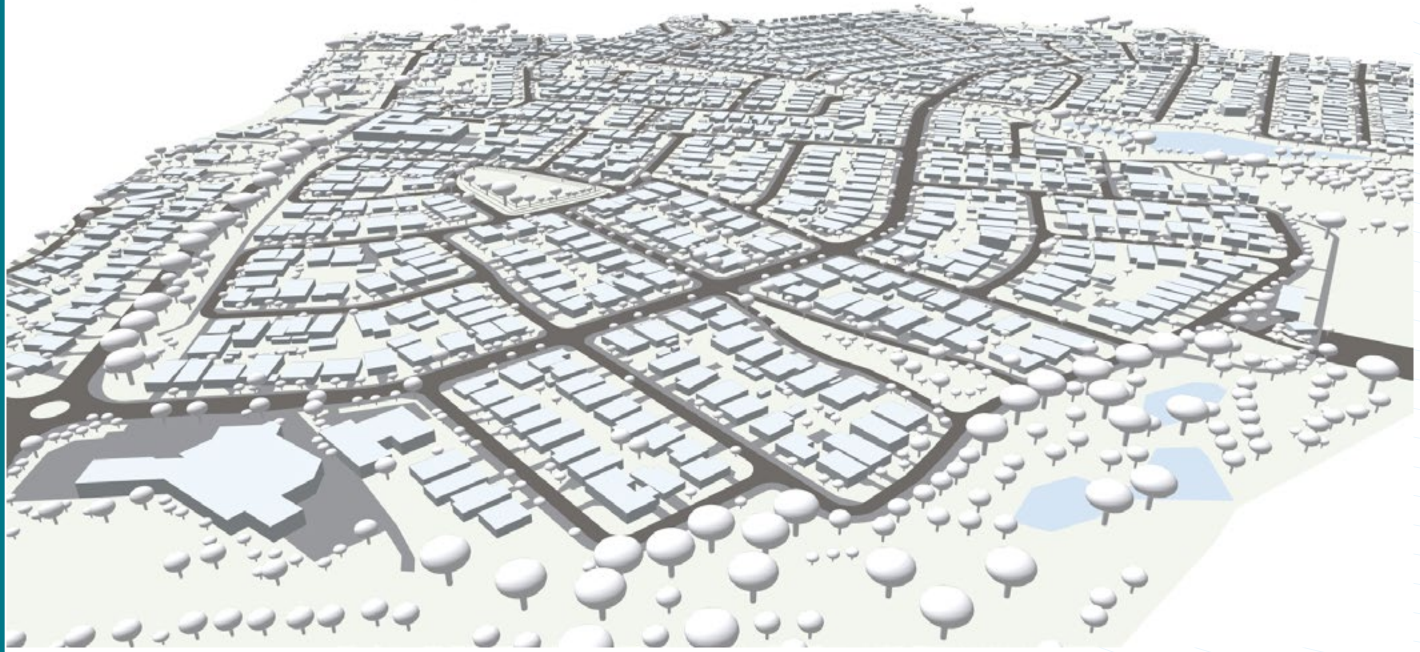


Figure B-20. Modelled base case of the existing conditions of Aberglasslyn.

Figure B-21. Simulated air temperature distribution of the existing base case conditions of Aberglasslyn at 2pm.

- Cooling Potential of Increasing Public and Private Greenery -

The existing greenery conditions of Aberglasslyn offered opportunities to increase the proportion of public and private greenery across the precinct. This cooling intervention scenario represents the maximum cooling potential through increased greenery in Aberglasslyn, which was a 7.7% increase in the precinct's total proportion of public and private greenery. Figure B-22 shows the location and scale of this additional greenery, which was primarily along the wider streets and in the public green spaces due to the reduced opportunities within the residential lots. These additional trees were based on the defined tree properties shown in Table B-4, and included predominantly medium-sized trees in public areas and small and medium-sized trees in private areas.

Figure B-23 presents the air and surface temperature reduction distributions at 2pm and 9pm for increasing public and private greenery in Aberglasslyn. During the day, the potential air temperature cooling impact was evenly distributed across the precinct with the greatest cooling impact resulting from the additional street trees along the wider streets. These additional street trees also enabled significant surface temperature reductions during the day by increasing the shading of these hard surfaces. During the evening, there was still a cooling benefit in air and surface temperature from increasing public and private greenery across Aberglasslyn, but the impact was relatively limited (Figure B-23).

Figure B-24 shows the hourly maximum air and surface temperature reductions possible from increasing public and private greenery in Aberglasslyn. A maximum air temperature reduction of 2.5 °C was achieved between 11am and 1pm, and a maximum surface temperature of more than 20 °C was achieved between 12pm and 3pm. During the evening, the maximum cooling potential is stable but limited to approximately a 0.75 °C reduction in air temperature, and less than a 5 °C reduction in surface temperature (Figure B-24).

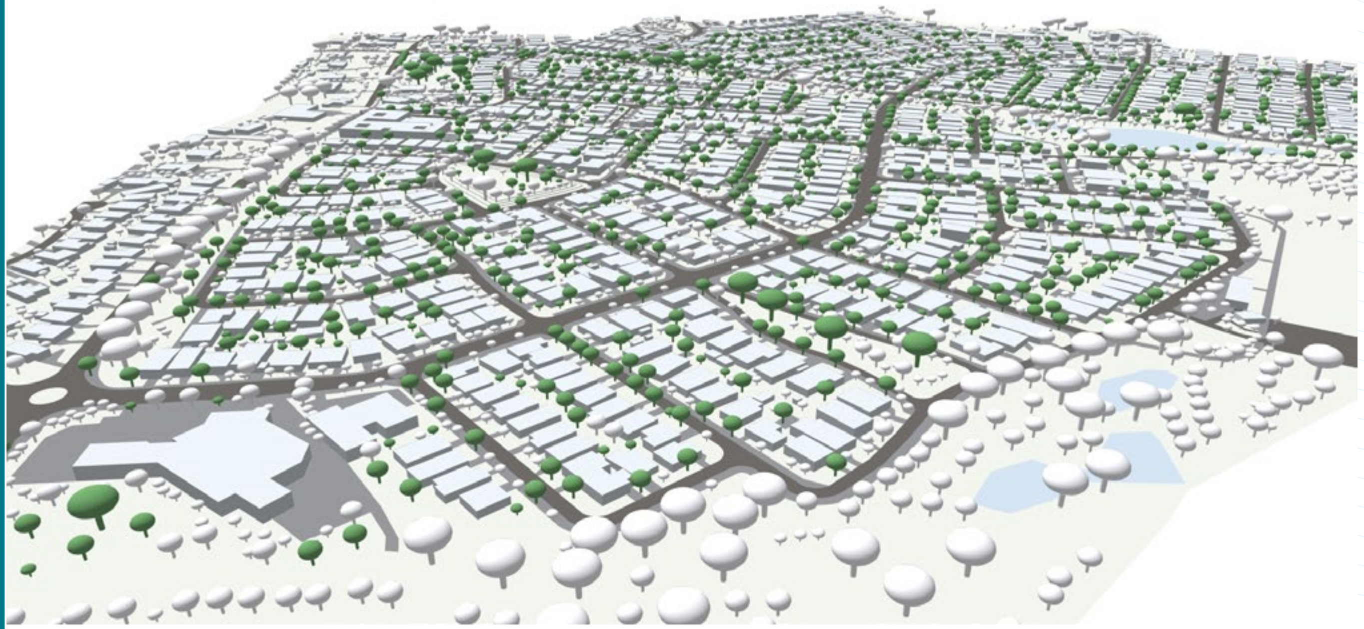


Figure B-22. Increased public and private greenery (shown in green) in Aberglasslyn.

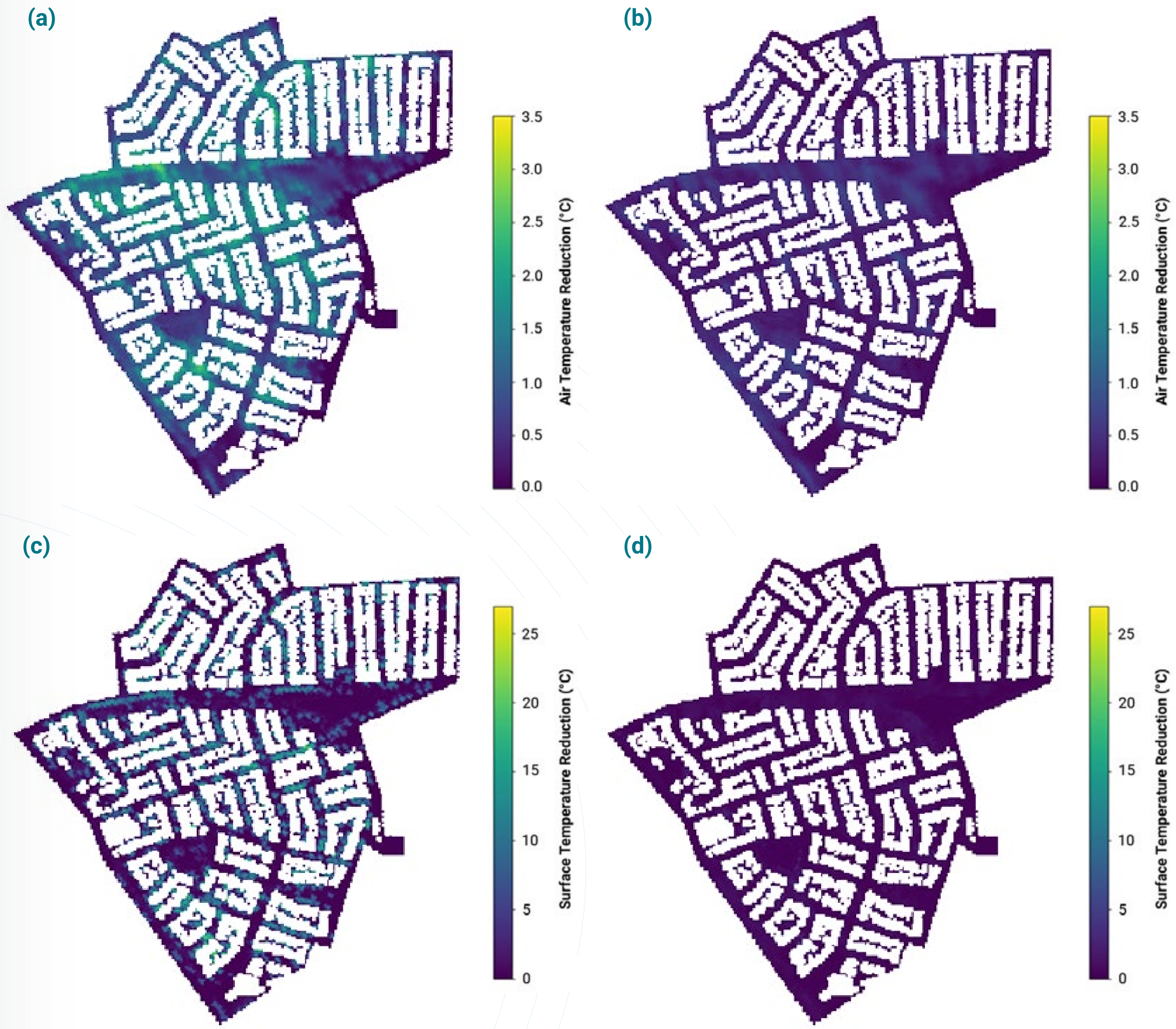


Figure B-23. Air temperature reduction distributions at (a) 2pm and (b) 9pm; and surface temperature reduction distributions at (c) 2pm and (d) 9pm; from increasing public and private greenery across Aberglasslyn.

Figure B-24. Hourly maximum (a) air temperature and (b) surface temperature reductions from increasing public and private greenery across Aberglasslyn.

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- Cooling Potential of Cool Materials for All Roads, Footpaths and Private Hard Surfaces -

Aberglasslyn aligns with the typical low-density residential development typology in NSW and Australia, and therefore requires a substantial road network to support the high proportion of private motor vehicles. As outlined in Section B.5.3, these asphalt roads, combined with the concrete footpaths and private hard surfaces, can exacerbate local urban overheating. In addition to shading these hard surfaces with increased greenery, another effective cooling intervention is to change the material properties of these hard surfaces to increase their albedo and emissivity, which transforms them into cool materials. This cooling intervention scenario represents the maximum cooling potential of changing all roads, footpaths and private hard surfaces in Aberglasslyn to be cool materials (Figure B-25) based on the cool road and pavement material properties outlined in Table B-3.

Figure B-26 shows the air and surface temperature reduction distributions at 2pm from applying cool materials for all roads, footpaths and private hard surfaces in Aberglasslyn, and Figure B-27 shows its hourly maximum air and surface temperature reductions throughout the selected simulation day. Naturally, the cooling impact of applying these cool materials was higher on the wider unshaded streets and during the middle of the day with high solar radiation. The maximum air and surface temperature reductions of this scenario were 1.1 °C and 10.5 °C respectively at 12pm. These findings show that the application of cool materials in Maitland's suburban context were generally less effective than increasing public and private greenery. This is likely attributed to the larger proportion of pervious surfaces across Aberglasslyn's low-density residential context, thereby limiting the cooling benefit of cool materials but offering greater opportunities for increasing tree canopy coverage. It is worth noting that in inner-city and dense urban contexts with higher proportions of hard surfaces, the cooling benefit of applying cool materials for roads and footpaths will increase. The cooling impact of the cool materials during the evening was very minor as the effectiveness of cool roads, pavements, and other hard surfaces is generally determined by its ability to reflect direct solar radiation.

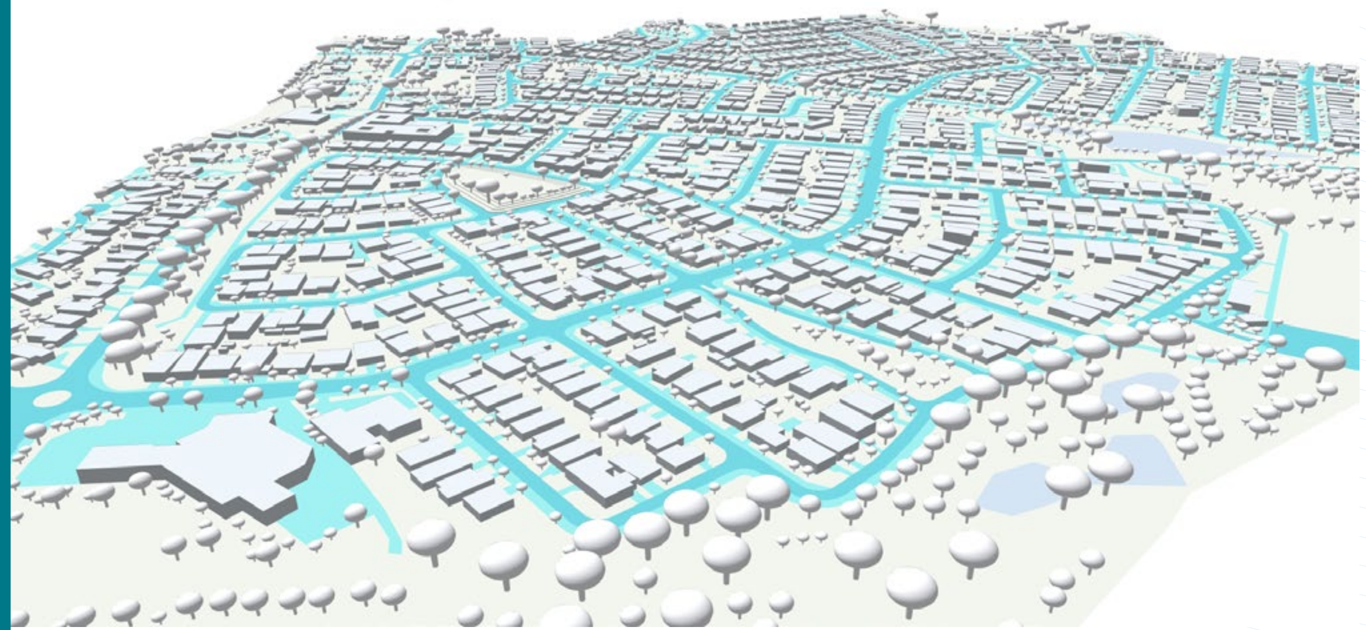

Figure B-25. Cool materials for all roads, footpaths and private hard surfaces (shown in blue) in Aberglasslyn.

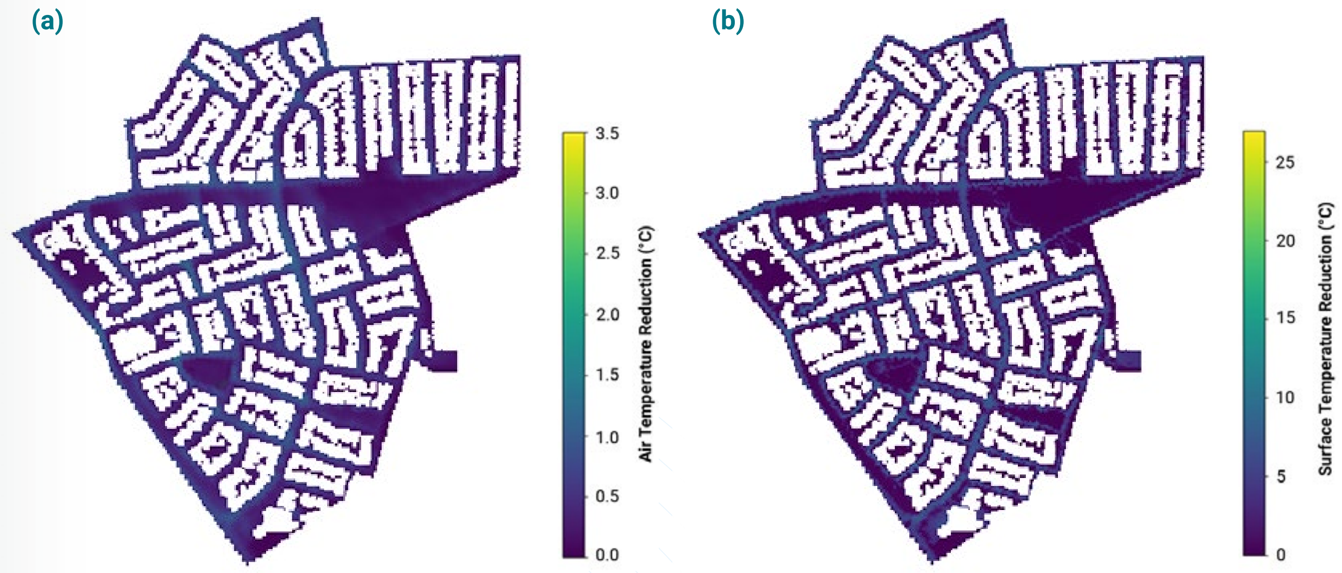

Figure B-26. (a) Air temperature and (b) surface temperature reduction distributions at 2pm from applying cool materials to all roads, footpaths and private hard surfaces in Aberglasslyn.

Figure B-27. Hourly maximum (a) air temperature and (b) surface temperature reductions from applying cool materials to all roads, footpaths and private hard surfaces in Aberglasslyn.

- Cooling Potential of Cool Roofs for All Buildings -

As mentioned previously, Aberglasslyn has a high proportion of dwellings with dark roof materials, which leads to high surface temperatures during extreme heat conditions. Like the previous scenario, changing the material properties of these roofs to be cool roofs can be an effective cooling intervention strategy, especially for the indoor thermal environment and subsequent cooling energy demand (which is shown in the next scenario). This cooling intervention scenario represents the maximum cooling potential of changing all roofs to be cool materials (Figure B-28) based on the cool roof material properties outlined in Table B-3.

Figure B-29 shows that the air temperature reduction distribution from having all buildings with cool roofs was evenly distributed but the scale of reductions is minor. The reason for this is that the air temperature reductions are for pedestrian-level air temperature, which is well below the roof level of the one and two-storey dwellings in Aberglasslyn. Although the magnitude of cooling potential was limited at the pedestrian level, Figure B-30 shows that the maximum air temperature reductions of 0.32 °C from applying these cool roofs on all buildings occurred during the early evening. This is largely due to increasing the emissivity of the metal roofs in Aberglasslyn from 0.6 to 0.85 to make them cool roofs.

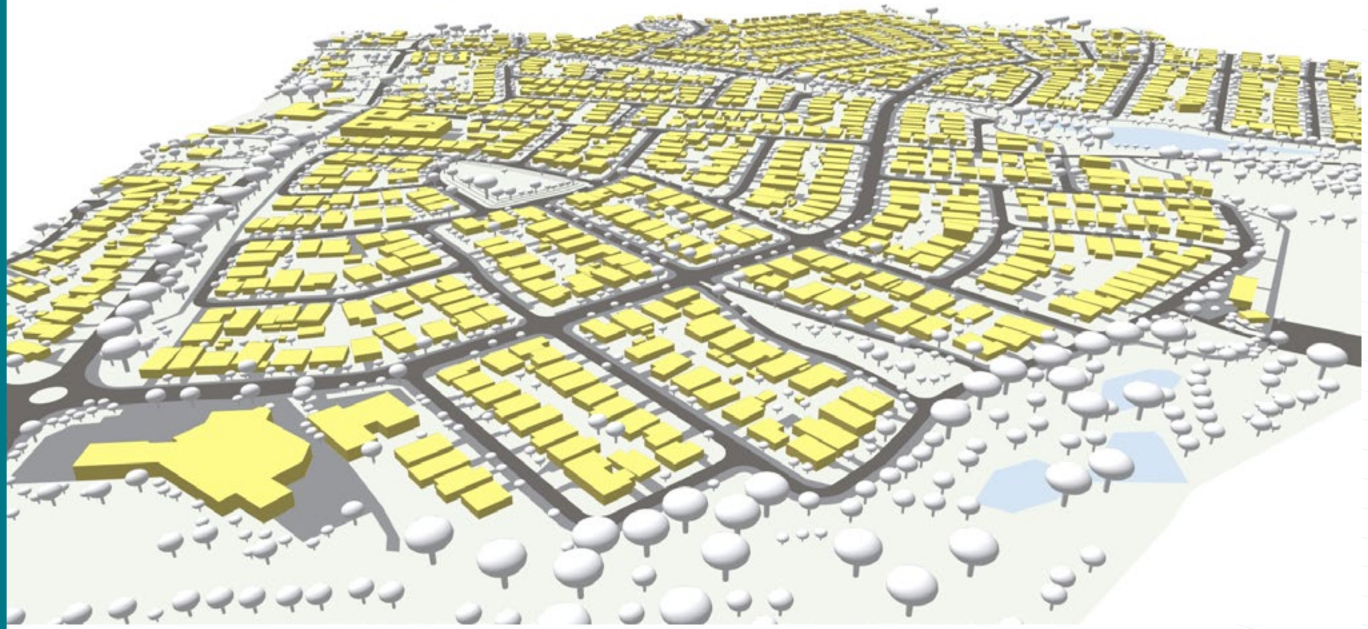

Figure B-28. Cool roofs for all buildings (shown in yellow) in Aberglasslyn.

Existing dark roofs of Aberglasslyn (Nearmap).

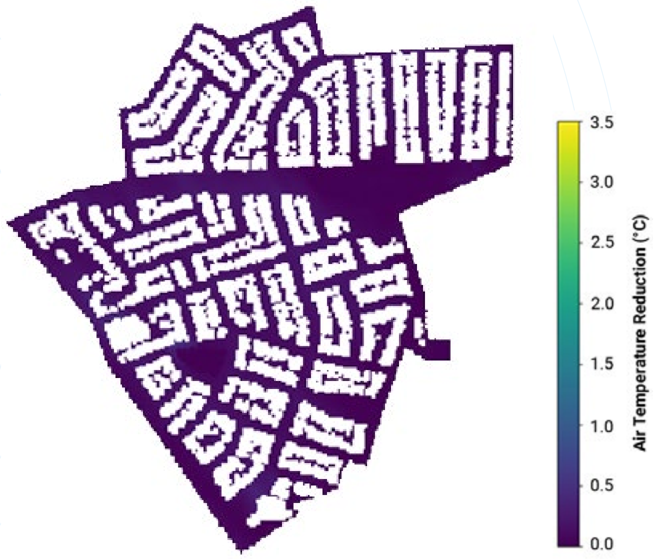

Figure B-29. Air temperature reduction distribution at 2pm from applying cool roofs to all buildings in Aberglasslyn.

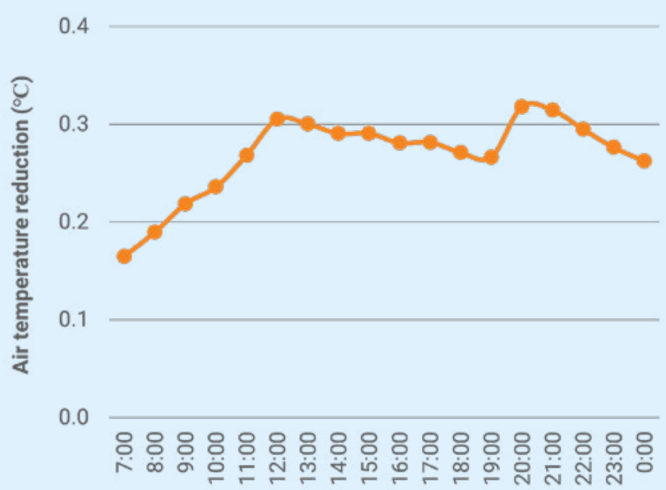

Figure B-30. Hourly maximum air temperature reductions from applying cool roofs to all buildings in Aberglasslyn.

- Energy Savings Potential of Cool Roofs in Aberglasslyn -

Using a representative single detached dwelling in Aberglasslyn as a case study, the energy savings potential of changing to a cool roof was calculated. This representative house was a 4-bedroom single storey detached house with a dark tiled roof, a brick-veneer wall construction type, and single glazed windows. Using the building's floor plan, a 3D model of the Aberglasslyn case study house was constructed in DesignBuilder to conduct a detailed energy analysis (Figure B-31). BOM weather station data and monthly electricity bills provided by the home's occupants were used by the research team to calibrate the initial analysis to be as close to reality as possible. Two additional scenarios were then analysed by changing the roof material to be a light-coloured roof, and a cool roof.

Figure B-32 shows the monthly total heating and cooling energy consumption for this case study house in Aberglasslyn with its original dark tiled roof and changing it to a light-coloured roof and a cool roof. These results show that significant energy savings were possible in the warmer months, but a heating penalty occurred during the cooler months. More specifically, there was an annual cooling energy consumption saving of 3.6% and 15.4% by changing to a light-coloured roof and a cool roof respectively, but an annual heating energy consumption increase of 2.4% and 11.6%. However, Figure B-33 shows that the magnitude of cooling energy savings in summer from changing to a cool roof outweighed the heating energy penalty, resulting in a predicted total annual energy saving of 37.9 kWh. Using this case study house as a template, if all houses in Aberglasslyn were to install cool roofs,

Figure B-31. Case study house in Aberglasslyn used to conduct detailed energy savings analysis of cool roofs.

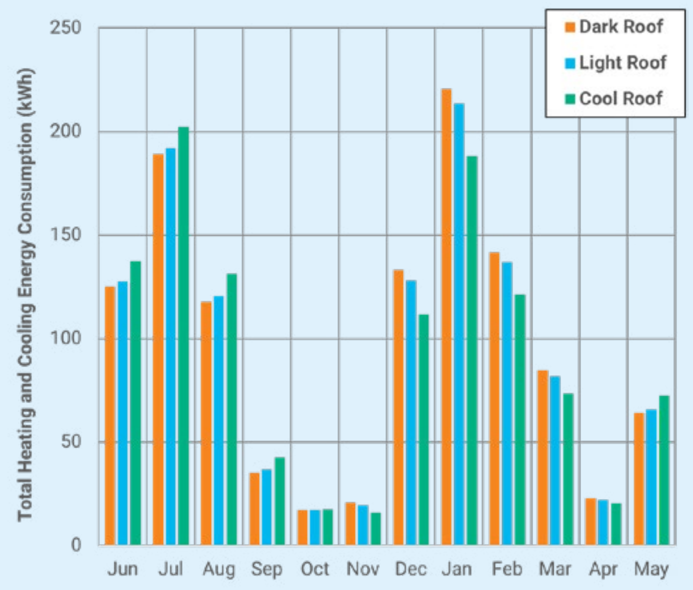

Figure B-32. Total monthly heating and cooling energy consumption for the Aberglasslyn case study house with different roof materials.

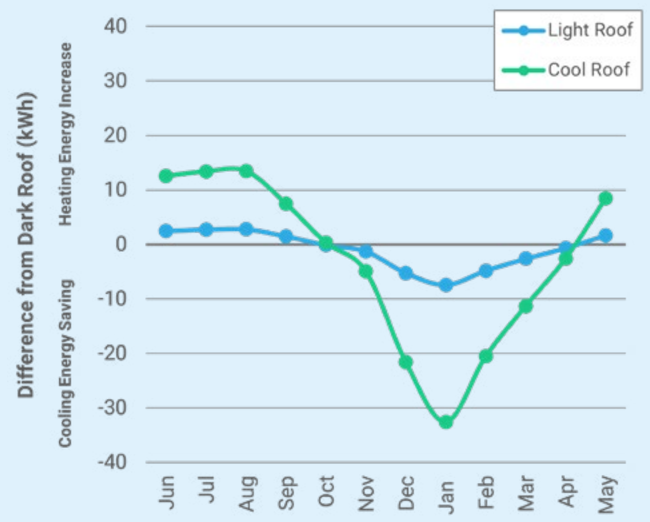

Figure B-33. Changes in monthly heating and cooling energy consumption for cool and light-coloured roofs as compared to a dark roof for the Aberglasslyn case study house.

an estimated total of 53.2 MWh of cooling energy savings were possible during the warmer months each year, which also equated to a carbon emission saving of 38.8 tCO_2e. When the heating penalty was applied to this, a total estimated annual energy saving of 14.9 MWh was achieved, which equated to an annual carbon emission saving of 10.9 tCO_2e. This estimation accounted for the proportion of houses in Aberglasslyn with light and dark roofs taken from the NaHVO Index datasets, and for 10% of houses with solar panels that can offset their cooling energy demands. UNSW researchers are now exploring super cool roof materials, which can provide significant cooling energy savings with a lower heating penalty[55, 56]. These super cool roof materials can also be coloured to reduce glare and provide aesthetic flexibility for residents beyond the traditional white or light-coloured roofs[57].

- Cooling Potential of a Combination of All Interventions Including Water Misting and Outdoor Shading -

This final cooling intervention scenario for Aberglasslyn represents the maximum cooling potential from a combination of mitigation scenarios. This included the increased public and private greenery and cool materials to all roofs, roads, pavements, and private hard surfaces from the previous scenarios (Figure B-34). This combined scenario also included the addition of outdoor shading and water misting located based on existing hot spots throughout Aberglasslyn. This cooling intervention scenario therefore shows the maximum possible cooling impact for Aberglasslyn without altering its existing built form, scale, and character.

Figure B-35 shows the air and surface temperature reduction distributions at 2pm from this combined mitigation scenario. These heatmaps show significant air and surface temperature cooling benefits equally distributed across the entire precinct. They also show the higher localised cooling benefits from the water misting and outdoor shading that were placed in existing hot spot areas throughout Aberglasslyn. Like the previous scenarios, the maximum cooling impact of this combination of mitigation strategies occurred during the middle of the day. Maximum air temperature reductions of approximately 3 °C were achieved between 11am to 2pm, and maximum surface temperature reductions above 20 °C were achieved between 12pm and 3pm (Figure B-36). There was also a minor but stable cooling benefit throughout the evening for both air and surface temperatures. This combination of mitigation scenarios reduced the NaHVO Index thermal heat vulnerability value from 9 to 8.

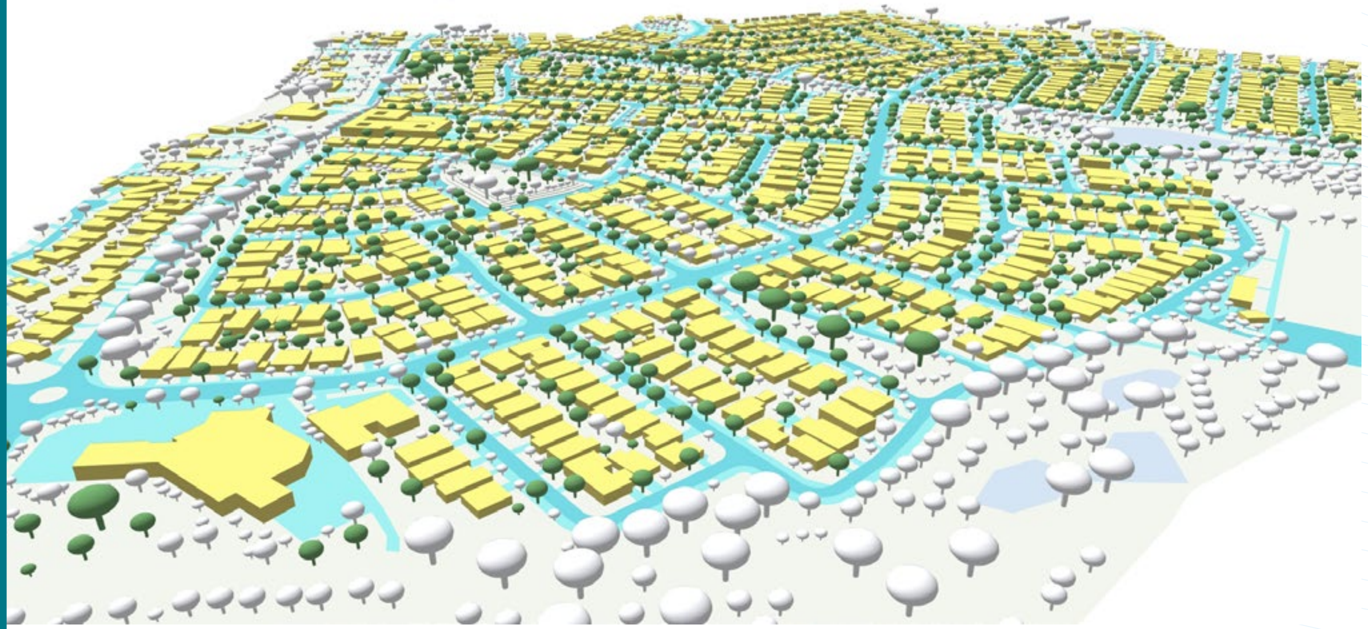

Figure B-34. Combination of all cooling interventions in Aberglasslyn (coloured as per previous scenarios).

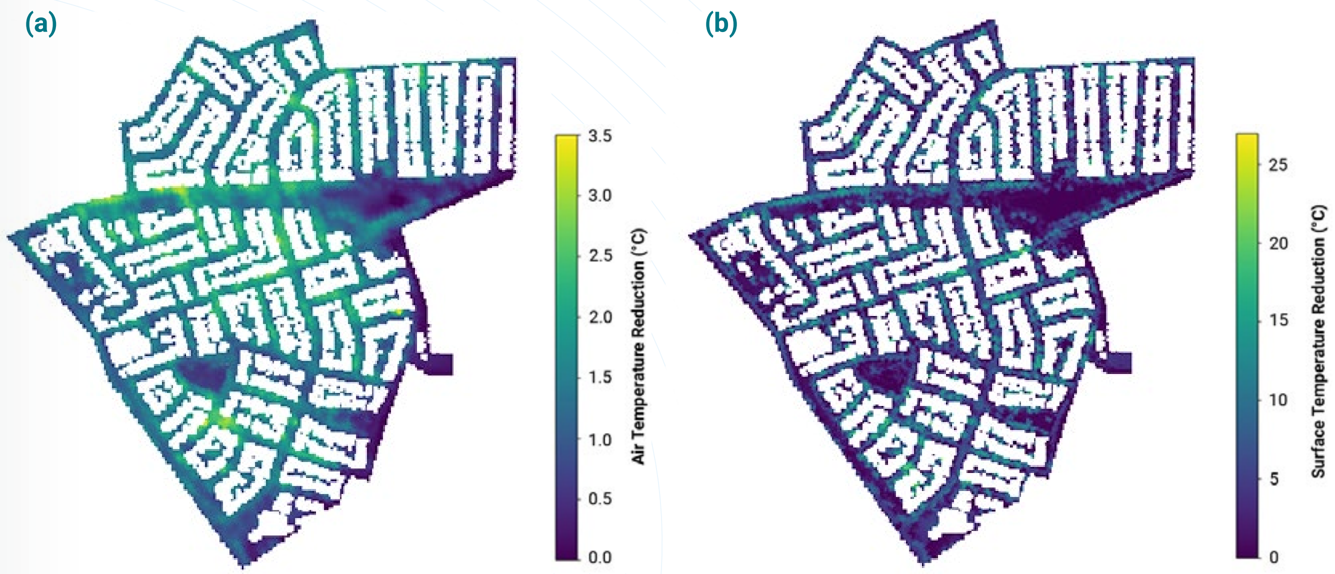

Figure B-35. (a) Air and (b) surface temperature reduction distributions at 2pm from a combination of all mitigation strategies including water misting and outdoor shading in Aberglasslyn.

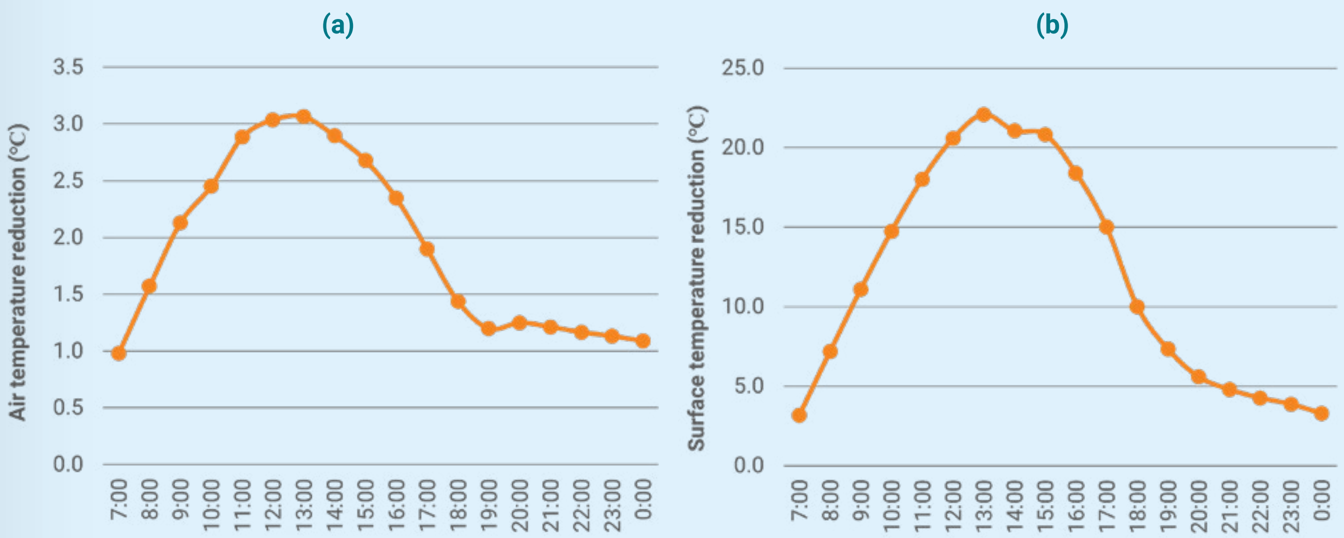

Figure B-36. Hourly maximum (a) air temperature and (b) surface temperature reductions from a combination of all mitigation strategies including water misting and outdoor shading in Aberglasslyn.

- Comparative Analysis of Mitigation Strategies for Aberglasslyn -

Figure B-37 presents a comparison of all cooling intervention strategies for Aberglasslyn, showing both maximum and average hourly air and surface temperature reductions. At all times of the day, a combination of mitigation scenarios produced the greatest cooling benefit for Aberglasslyn. These results reinforce the need for holistic and comprehensive measures to address heat vulnerability at the precinct scale, and not relying on a single cooling intervention. While the maximum cooling potential of a combined mitigation strategy can be similar to the increased greenery scenario, the average air and surface temperature reductions across the entire Aberglasslyn precinct demonstrate the combined mitigation scenario's increased effectiveness (Figure B-37). It is worth emphasising again that the reduced effectiveness of the cool materials scenario is primarily due to the lower proportion of hard surfaces in Aberglasslyn's residential development typology compared to more dense urban contexts. The cool roof scenario was not included in this comparison due to its limited effectiveness in reducing pedestrian-level air temperature, but cool roofs remain an important cooling intervention strategy to reduce indoor air temperatures and cooling energy demand during extreme heat events.

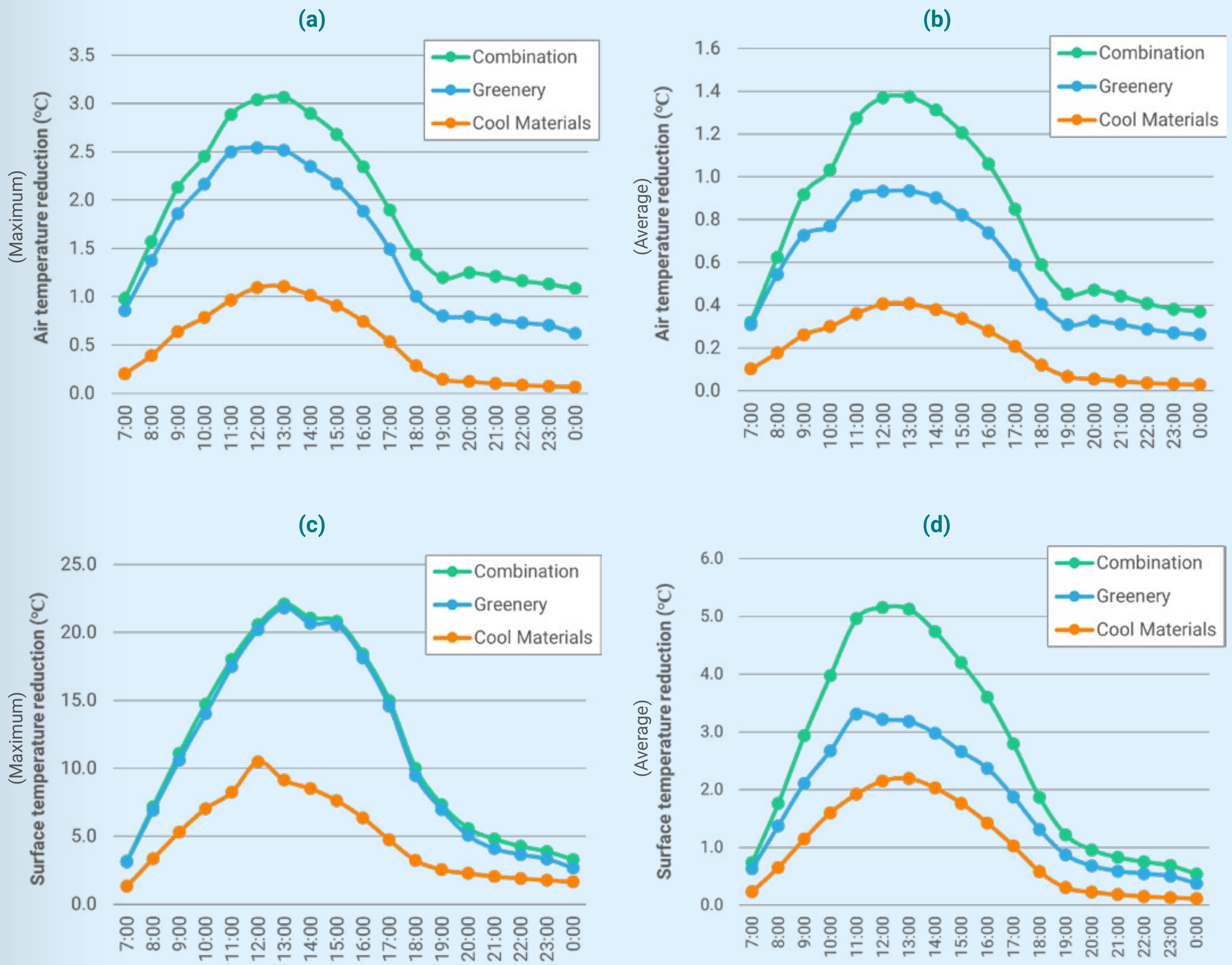

Figure B-37. Comparison of mitigation strategies for Aberglasslyn showing hourly (a) maximum and (b) average air temperature reductions, and hourly (c) maximum and (d) average surface temperature reductions.

B.5.4 Cooling Potential of Mitigation Strategies in Chisholm

Heat Vulnerability Challenges and Built Environment Characteristics of Chisholm

Another key area of interest for Maitland City Council regarding heat vulnerability was Chisholm. The primary reason for this is the juxtaposition of two distinct residential areas: an existing area with large, detached dwellings on significant portions of land with considerable tree canopy coverage and a minimal street network; and the other a typical new low-rise detached dwellings with predominantly dark roofs on smaller lots with narrow streets and reduced tree canopy coverage. Figure B-38 shows these differences in built environment characteristics translate to vast differences in surface temperatures. The extensive tree canopy

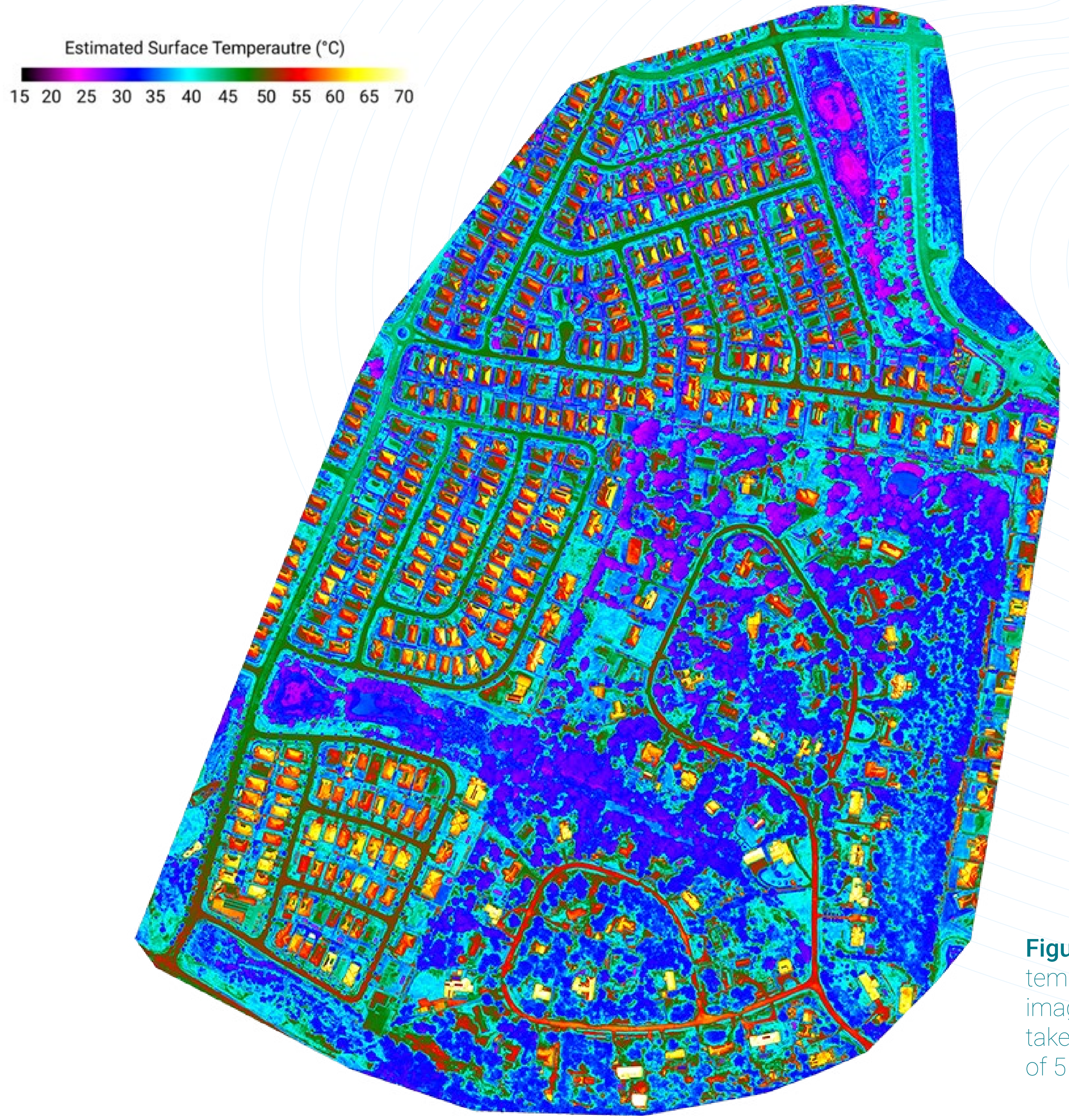

Figure B-38. Surface temperature thermal imagery of Chisholm taken on the afternoon of 5 December 2023.

View of Chisholm via drone aerial photography (UNSW High Performance Architecture).

of the existing areas is shown in purple and blue indicating lower surface temperatures, and the compact detached houses and unshaded streets in the newer development areas are shown in yellow and red indicating higher surface temperatures. Compared to the other case study precincts in the Phase 1 pilot of the NaHVO, Chisholm had the highest tree canopy coverage on average and the lowest total number of heatwave days across the defined study period. The detailed built environment characteristics and heat vulnerability challenges for Aberglasslyn are provided in Table B-7.

Chisholm was included in the Phase 1 pilot of the NaHVO to investigate the maximum cooling potential of the newer development areas and see how this compared to the existing area with higher tree canopy coverage. Accordingly, there are two heat mitigation scenarios for the Chisholm case study precinct, the base case of its existing conditions and a combination of mitigation strategies. The maximum cooling potential results of the combined mitigation scenario are presented in this section as reductions in air and surface temperature from the base case scenario for Chisholm.

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Figure B-39 shows the modelled existing conditions of Chisholm including 3D building objects and trees, road and footpath networks, and water bodies. This was generated from a wide range of data sources from Maitland City Council, open-source datasets, and satellite imagery (see Report D for more detail). This model of Chisholm was used to simulate a base case scenario, which formed the basis to compare the combined mitigation scenario against. As mentioned in Section B.5.1, this base case model was validated with on-site measurements for air temperature, relative humidity, wind speed and direction, and solar radiation to ensure the simulated results were as close as possible to reality.

Figure B-40 presents the air temperature distribution of the simulated base case at 2pm for the Chisholm case study precinct.

Table B-7. Built environment characteristics and heat vulnerability challenges in Chisholm.

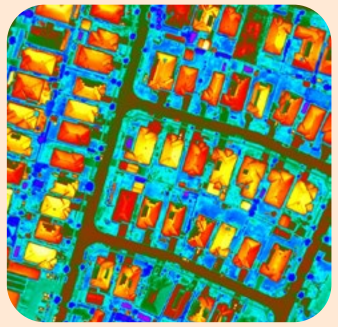
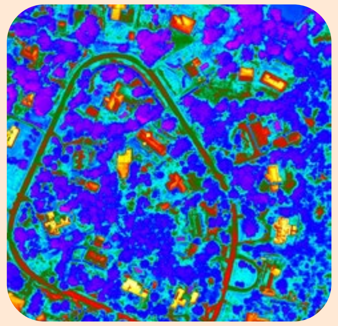
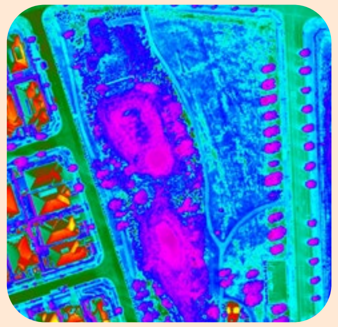
THERMAL IMAGERY	AERIAL IMAGERY	STREETSCAPE	BUILT ENVIRONMENT CHARACTERISTICS	HEAT VULNERABILITY CHALLENGES
			» Low-rise detached residential buildings with a compact layout. » Small to moderate areas of pervious and impervious private open space with limited trees. » Narrow roads with low street tree canopy coverage. » High proportion of dark-coloured roofs.	» Exposed private open space due to limited private tree canopy. » Exposed hard surfaces with high surface temperatures along streets from limited tree canopy. » Narrow roads limit the opportunities for raingardens and outdoor shading. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Low-rise detached residential buildings with a sparse layout. » Large area of private pervious surfaces with significant tree canopy coverage. » Narrow and sparse road network with well-established street trees. » Moderate proportion of dark-coloured roofs.	» Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days. » Some exposed road surfaces with high surface temperatures.
			» Linear green open space with a small water body and limited tree canopy coverage.	» Small water bodies can only provide a limited cooling effect for its immediate surroundings. » Areas of unirrigated and unshaded grass have relatively higher surface temperatures.

Figure B-39. Modelled base case of the existing conditions of Chisholm.

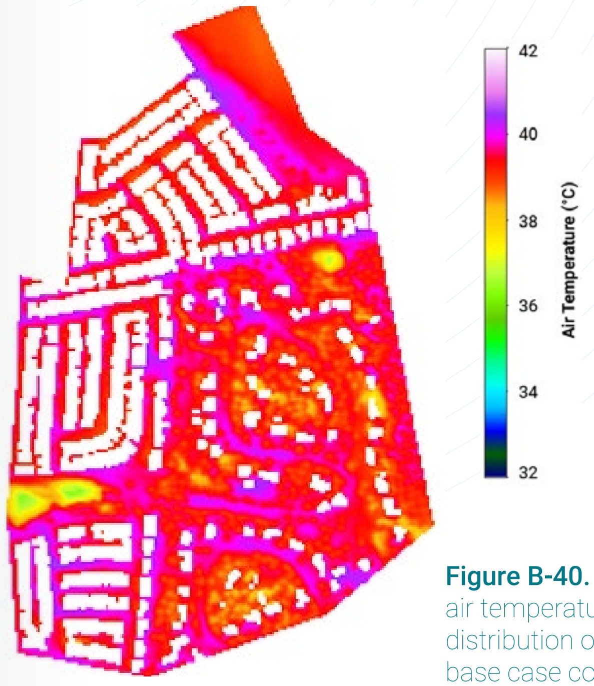


Figure B-40. Simulated air temperature distribution of the existing base case conditions of Chisholm at 2pm.

This clearly shows the difference in air temperature between the two residential typologies within this precinct. The vast tree canopy coverage of the existing residential area, shown in yellow, was approximately 2 to 3 °C less than the newer more compact residential areas surrounding it (Figure B-40). The water bodies and public parks also showed a localised cooling benefit for their immediate surroundings.

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This scenario involves a combination of heat mitigation strategies for Chisholm (Figure B-41). Firstly, this scenario added public and private greenery in the newer residential development areas, increasing its total tree canopy coverage by 3.3%. Secondly, it applied cool materials to all roofs, roads, pavements, and private hard surfaces. Lastly, this scenario included the addition of outdoor shading and water misting located based on existing hot spots throughout Chisholm. This cooling intervention scenario therefore represents the maximum possible cooling impact for Chisholm without altering its existing built form, scale, and character.

Figure B-42 shows the air and surface temperature reduction distributions at 2pm from this combined mitigation scenario for Chisholm. These heatmaps show significant air and surface temperature reductions for the newer compact residential development areas of Chisholm, as this was where the combination of mitigation strategies was primarily applied in this scenario. Minor air and surface temperature reductions were also evident for the existing residential areas from the addition of cool materials for the building roofs and the roads and pavements. The maximum cooling potential occurred between 12pm and 1pm in the newer compact residential areas, with air and surface temperature reductions of 2.7 °C and 19.7 °C respectively (Figure B-43).

Figure B-41. Combination of all cooling interventions in Chisholm (coloured as per previous scenarios for Aberglasslyn).

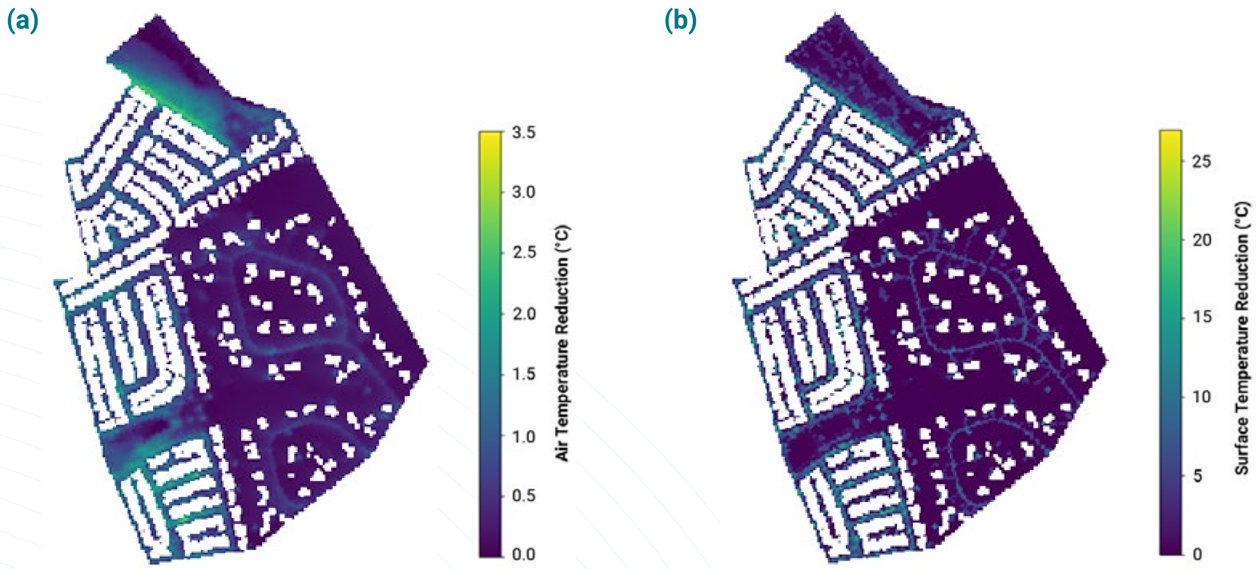

Figure B-42. (a) Air and (b) surface temperature reduction distributions at 2pm from a combination of all mitigation strategies including water misting and outdoor shading in Chisholm.

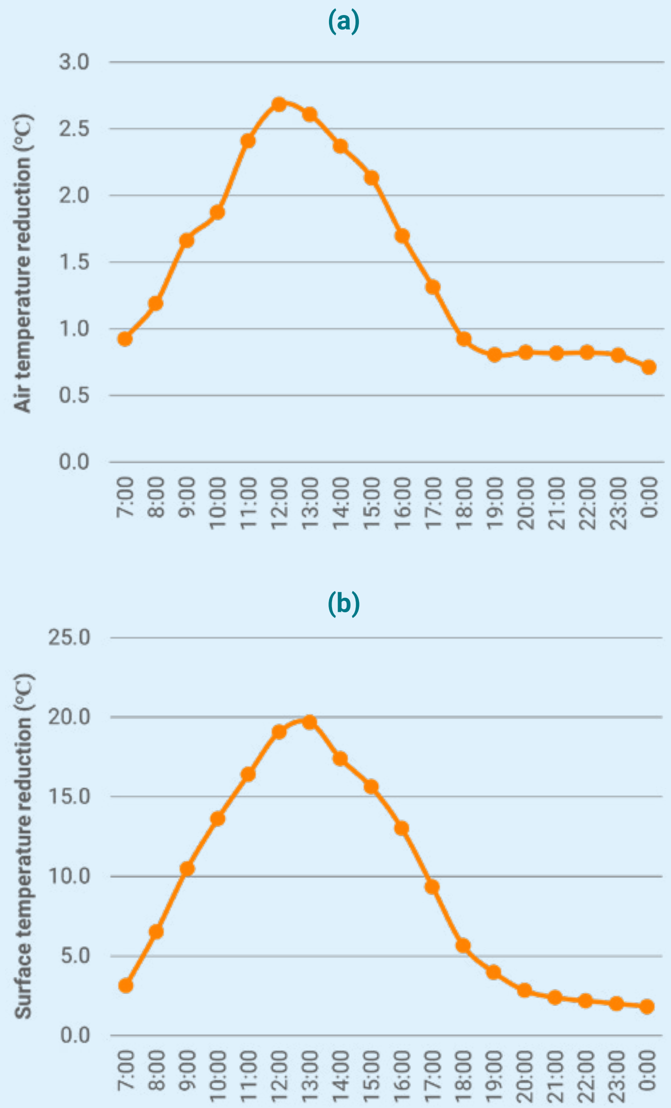

Figure B-43. Hourly maximum (a) air temperature and (b) surface temperature reductions from a combination of all mitigation strategies including water misting and outdoor shading in Chisholm.

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B.5.5 Cooling Potential of Mitigation Strategies in Gillieston Heights

Heat Vulnerability Challenges and Built Environment Characteristics of Gillieston Heights

Gillieston Heights was the final precinct identified by Maitland City Council to investigate its heat vulnerability and cooling potential. It comprises a diverse mix of low-rise residential development typologies with unique built environment characteristics. The north-east portion of Gillieston Heights includes the typical new residential development typology seen throughout Maitland with higher proportions of dark roofs and lower public and private tree canopy coverage (shown in red and yellow in Figure B-44). The north-west of Gillieston Heights is currently under construction, but the simulations included built environment features within this area that were aligned with this typical new residential development typology. To the south-west are older and smaller residential detached dwellings on slightly larger parcels of land. This results in higher proportions of pervious surfaces and private tree canopy coverage (shown in light and dark blue in Figure B-44). Finally, in the centre of the Gillieston Heights precinct is a dense gated retirement village with lower-quality detached housing. Despite this area having predominantly light-coloured roofs (shown in light blue in Figure B-44), it represents (using the NaHVO Index datasets) a high concentration of vulnerable people based on their age, income, health, education, and social disadvantage. The detailed built environment characteristics and heat vulnerability challenges for Gillieston Heights are provided in Table B-8.

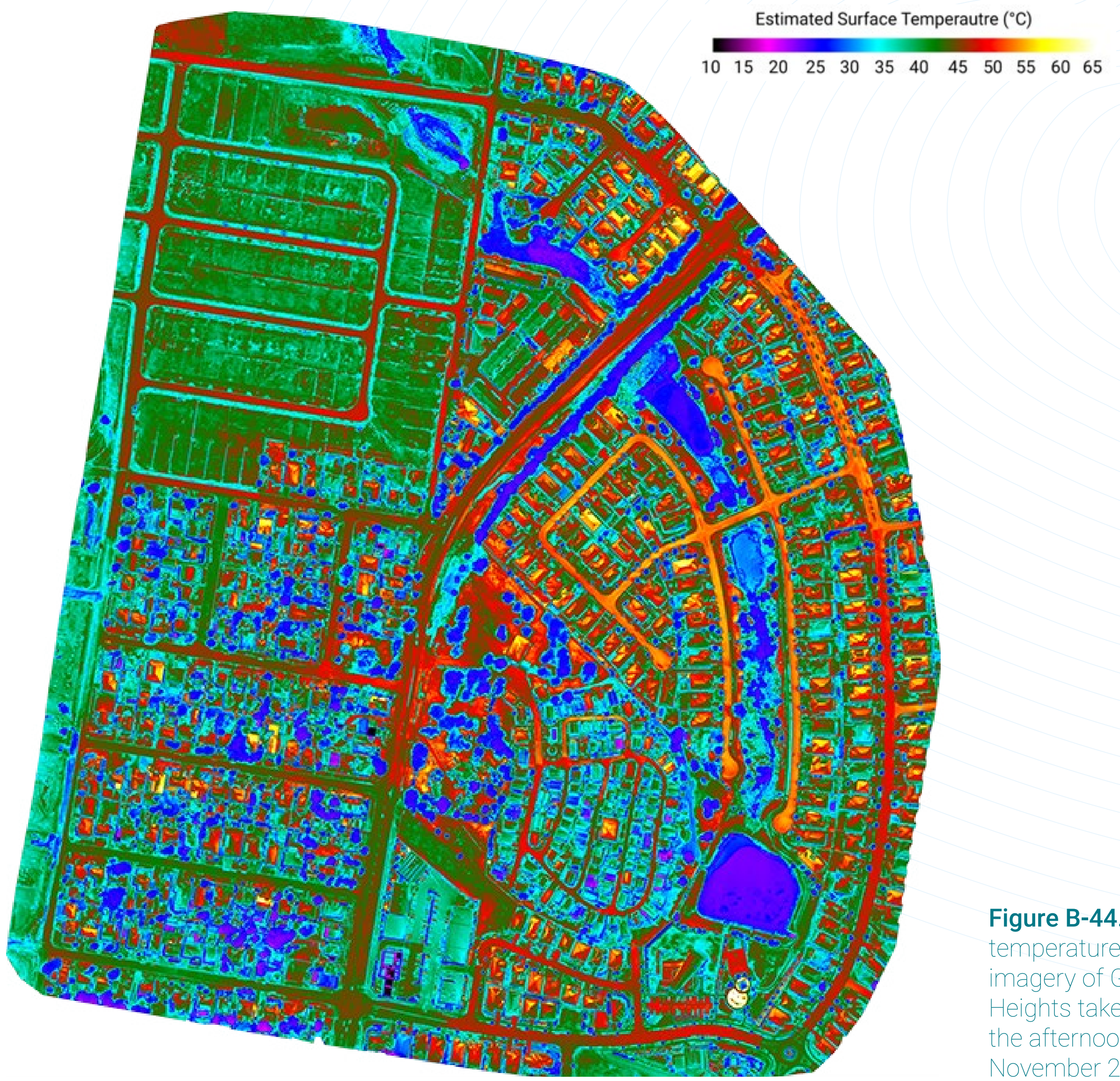


Figure B-44. Surface temperature thermal imagery of Gillieston Heights taken on the afternoon of 6 November 2023.

View of Gillieston Heights via drone aerial photography (UNSW High Performance Architecture).

Gillieston Heights was included in the Phase 1 pilot of the NaHVO to investigate the maximum cooling potential across these diverse residential typologies. Like the Chisholm case study precinct, there are two heat mitigation scenarios for Gillieston Heights. First, the base case of its existing conditions, and second, a combination of mitigation strategies. The maximum cooling potential results of the combined mitigation scenario are presented in this section as reductions in air and surface temperature from the base case scenario for Gillieston Heights.

Table B-8. Built environment characteristics and heat vulnerability challenges in Gillieston Heights.

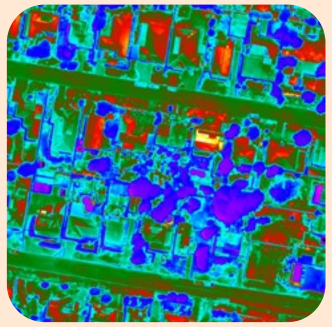
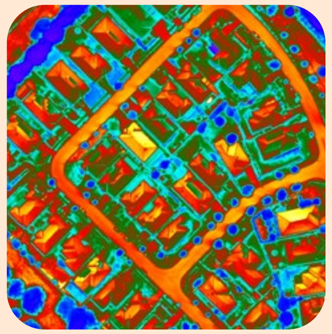
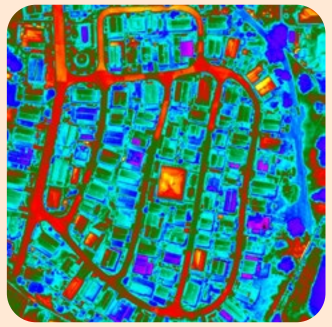
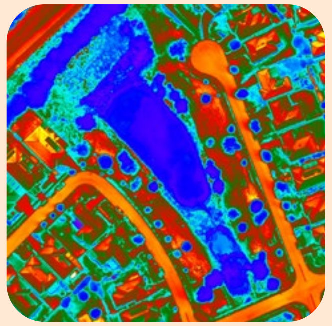
THERMAL IMAGERY	AERIAL IMAGERY	STREETSCAPE	BUILT ENVIRONMENT CHARACTERISTICS	HEAT VULNERABILITY CHALLENGES
			» Low-rise detached residential buildings with higher proportions of private green space and tree canopy coverage. » Moderate street tree canopy coverage. » Low to moderate proportion of dark-coloured roofs.	» Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days. » Some exposed road surfaces with high surface temperatures.
			» Low-rise detached residential buildings with a compact layout. » Small to moderate areas of pervious and impervious private open space with limited trees. » Narrow roads with low street tree canopy coverage. » High proportion of dark-coloured roofs.	» Exposed private open space due to limited private tree canopy. » Exposed hard surfaces with high surface temperatures along streets from limited tree canopy. » Narrow roads limit the opportunities for raingardens and outdoor shading. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Dense gated retirement village with lower-quality housing. » High proportion of light-coloured roofs.	» High concentration of vulnerable people in relation to their age, income, education, and health, living in lower-quality buildings (from NaHVO Index datasets).
			» Linear green open space with small water bodies and low to moderate tree canopy coverage.	» Areas of unirrigated and unshaded grass have higher surface temperatures. » Small water bodies can only provide a limited cooling effect for its immediate surroundings.

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Figure B-45 shows the modelled existing conditions of Gillieston Heights including 3D building objects and trees, road and footpath networks, and water bodies. This was generated from a wide range of data sources from Maitland City Council, open-source datasets, and satellite imagery (see Report D for more detail). This model of Gillieston Heights was used to simulate a base case scenario, which formed the basis to compare the combined mitigation scenario against. As mentioned in Section B.5.1, this base case model was validated with on-site measurements for air temperature, relative humidity, wind speed and direction, and solar radiation to ensure the simulated results were as close as possible to reality.

Figure B-46 presents the air temperature distribution of the simulated base case at 2pm for the Gillieston Heights case study precinct. This shows that high air temperatures were generally equally distributed across Gillieston Heights. However, the small water bodies within the public open spaces provided effective localised cooling impacts with air temperatures of approximately 2 to 3 °C less than other areas of the precinct.

Wallis Creek Park, Gillieston Heights (UNSW High Performance Architecture).

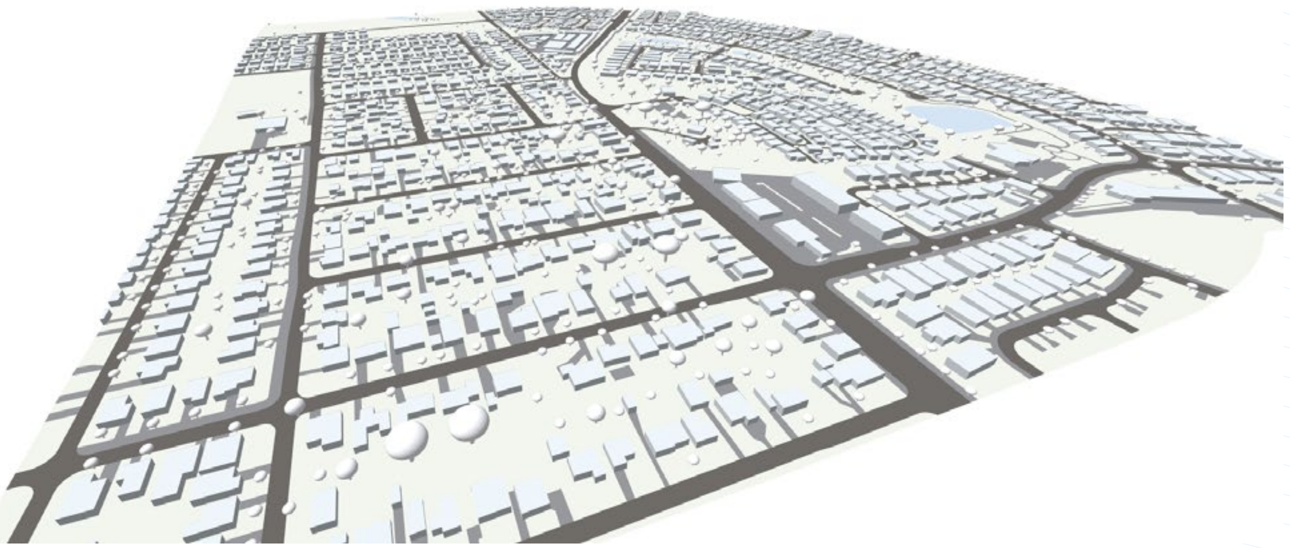

Figure B-45. Modelled base case of the existing conditions of Gillieston Heights.

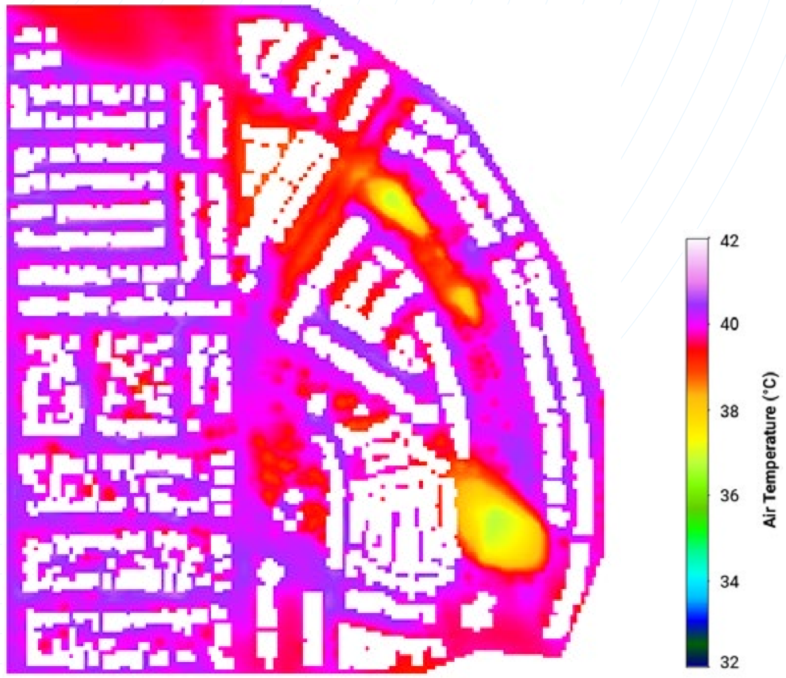

Figure B-46. Simulated air temperature distribution of the existing base case conditions of Gillieston Heights at 2pm.

- Cooling Potential of a Combination of All Interventions Including Water Misting and Outdoor Shading -

This scenario involves a combination of heat mitigation strategies for Gillieston Heights (Figure B-47). As the older residential areas have good private tree canopy coverage, the addition of private greenery was predominantly limited to the newer residential areas. Public greenery was added where possible throughout the precinct as well as the addition of raingardens in the middle of major roads, increasing the total tree canopy coverage in Gillieston Heights by 4.6%. This scenario also applied cool materials to all roofs, roads, pavements, and private hard surfaces and incorporated outdoor shading and water misting in existing hot spots throughout Gillieston Heights. This cooling intervention scenario therefore represents the maximum possible cooling impact for Gillieston Heights without altering its existing built form, scale, and character.

Figure B-48 shows the air and surface temperature reduction distributions at 2pm from this combined mitigation scenario for Gillieston Heights. These heatmaps show significant cooling benefits across the entire Gillieston Heights precinct, especially within the newer residential areas with added public and private greenery. They also show the higher localised cooling benefits from the addition of raingardens, water misting, and outdoor shading that were placed in existing hot spot areas throughout Gillieston Heights. The maximum cooling impact of this combination of mitigation strategies occurred during the middle of the day, with maximum air and surface temperature reductions of 3.1 °C and 26.1 °C respectively (Figure B-49). There was also a minor cooling benefit throughout the evening from this scenario.

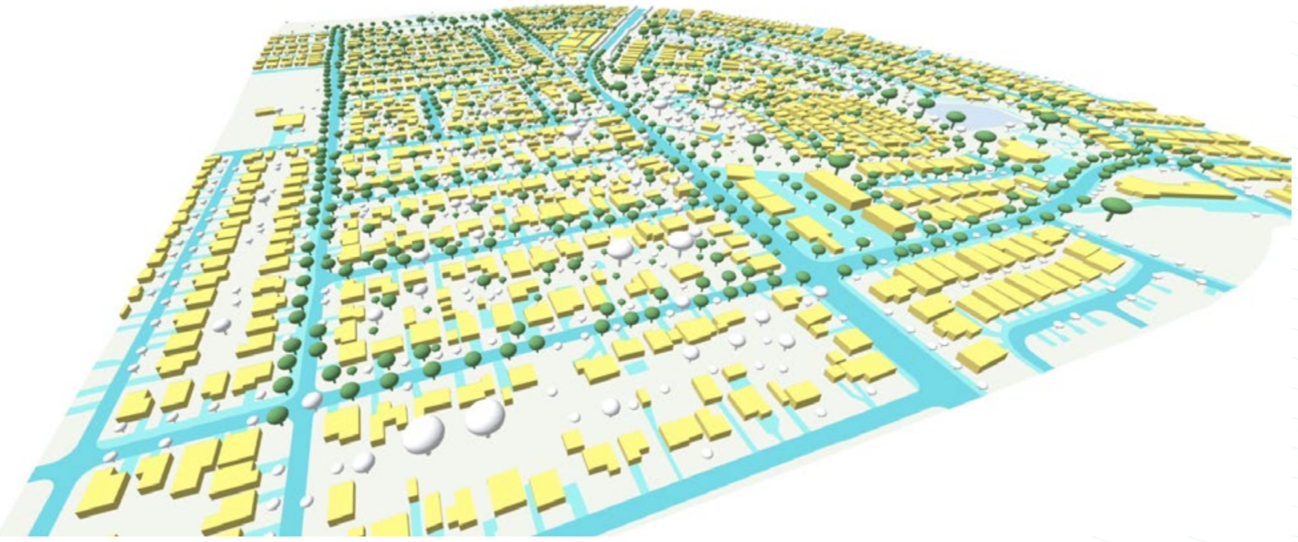

Figure B-47. Combination of all cooling interventions in Gillieston Heights (coloured as per previous scenarios for Aberglasslyn).

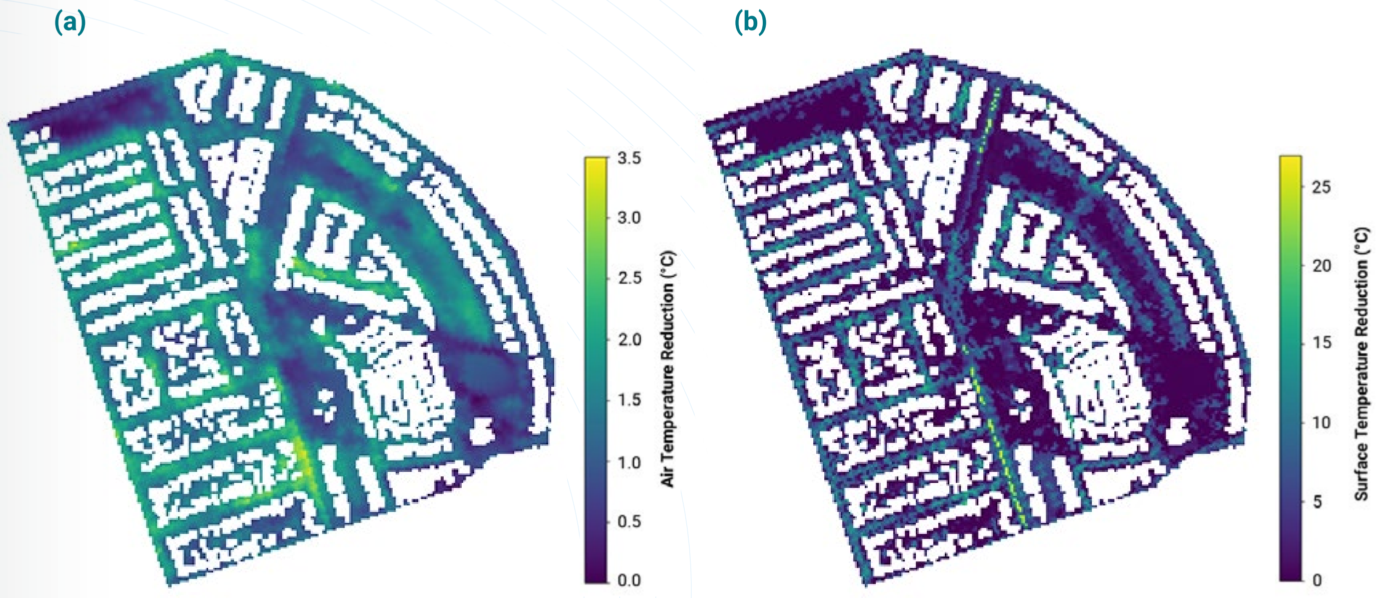

Figure B-48. (a) Air and (b) surface temperature reduction distributions at (a) 2pm from a combination of all mitigation strategies including water misting and outdoor shading in Gillieston Heights.

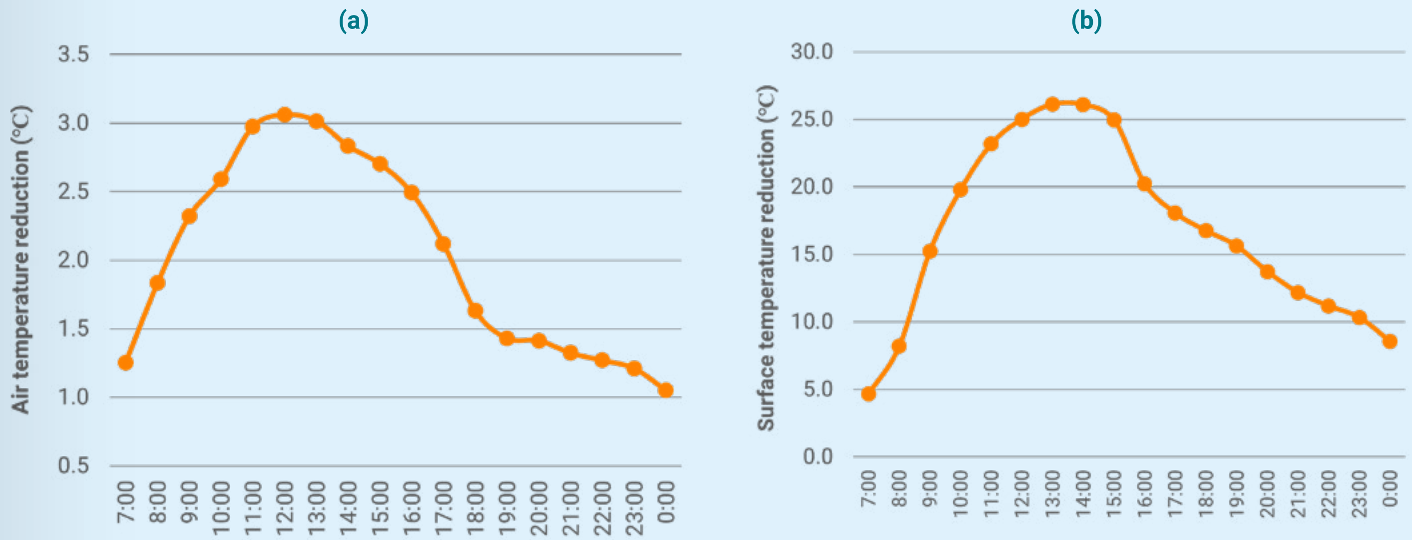

Figure B-49. Hourly maximum (a) air temperature and (b) surface temperature reductions from a combination of all mitigation strategies including water misting and outdoor shading in Gillieston Heights.

Report C: Dubbo Case Study

Victoria Park, Dubbo
(UNSW High Performance Architecture).

C.1 Local Climate in Dubbo

Dubbo is a major regional city in the Central West Orana Region of NSW. It has a humid subtropical climate, with warm to hot summers. The Dubbo Region experiences 20 – 30 hot days per year on average, during which severe fire weather conditions are likely in summer. Maximum temperatures in the Dubbo Region are projected to increase by 2.5 °C by 2070, see AdaptNSW. Figure C-1 shows a satellite image of the Dubbo Region, covering an area of approximately 32 km by 32 km.

The Urban Heat Island (UHI) intensity, defined as the temperature difference between a point within the city and a reference point in the suburb, ranges from 0.5 °C to 1.5 °C in the built-up area of the Dubbo Region during the daytime, diminishing slightly during the nighttime. The average temperatures in the western and built-up areas of the Dubbo Region surpass those in the eastern area, resulting in a notable spatial distribution of the Urban Heat Island (UHI).

Two heatwave periods, similar to the Maitland City case study, occurring before the COVID-19 outbreak, were identified for analysing the maximum cooling potential of mitigation options, thereby minimising the influence of COVID-19 on health and energy in the NaHVO Index. The identified heatwave periods were (1) 22/12/2019 - 06/01/2020 and (2) 18/01/2020-02/02/2020.

The daily air temperatures during the two heatwave periods in the built-up area in the Dubbo Region are presented in Figure C-2, where over 50% of the days had a daily maximum air temperature exceeding 35 °C. The median air temperature in the first heatwave period was 2.14 °C higher than in the second heatwave period in the Dubbo Region.

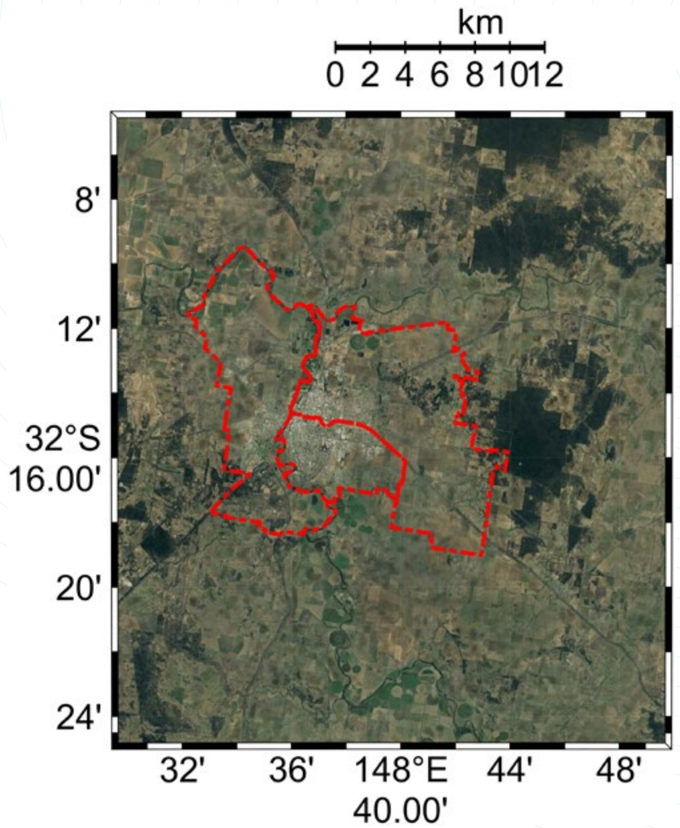

Figure C-1. A satellite image of the Dubbo Region covering an area of approximately 32km by 32km.

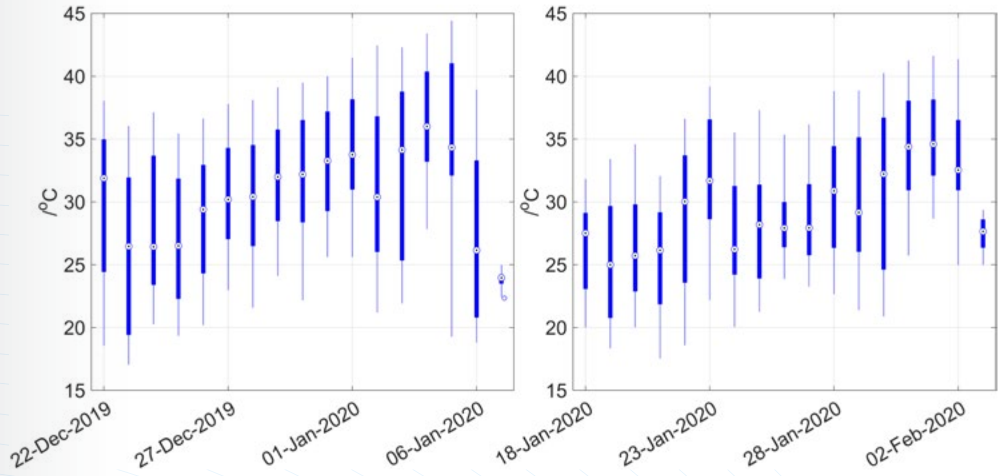

Figure C-2. (a) Daily air temperature range during the first heatwave period and (b) daily air temperature range during the second heatwave period. Where, the top of the blue box presents the 75% of air temperatures during the day, the bottom of the box presents the 25% of air temperatures during the day, and the middle point presents the median value.

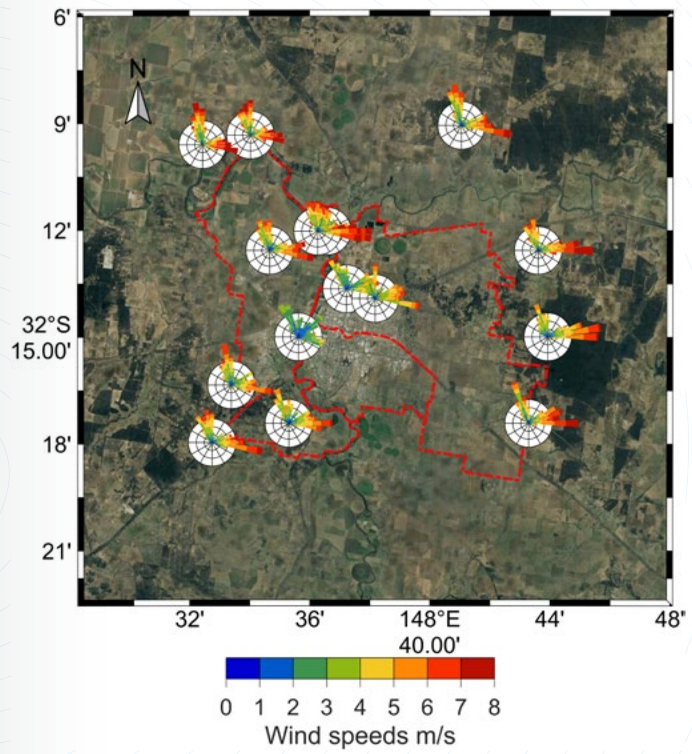

Figure C-3. Wind roses indicate the dominant wind directions during the two heatwave periods in the Dubbo Region.

The dominant wind direction during the two heatwave periods was from the east and north (Figure C-3), with speeds up to 8 m/s at a height of 10 m. Figure C-4 (a) presents the wind field characteristics over the terrain in the Dubbo Region, while Figure C-4 (b) presents the air temperature distribution at 2:00pm on a hot day (05/01/2020) during the first heatwave period. There were correlations between the air temperature distribution, terrain characteristics, and wind patterns, see Figure C-4. Most of the area had an air temperature exceeding 40 °C, and the air temperatures in the built-up and low-lying areas were higher than in other areas.

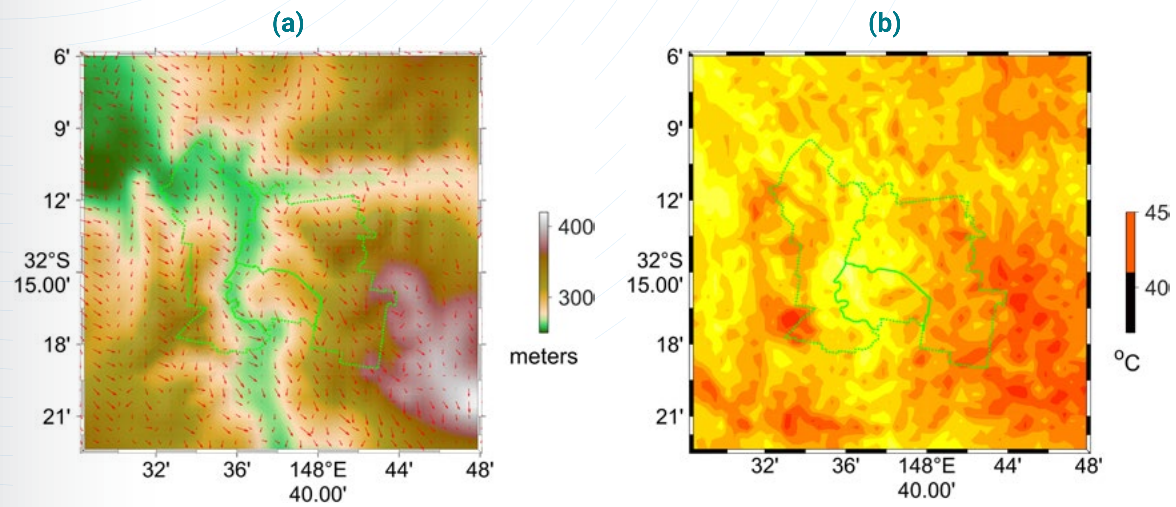

Figure C-4. (a) The wind field characteristics over the terrain in the Dubbo Region and (b) the air temperature distribution at 2:00pm on a hot day (05/01/2020) during the first heatwave period.

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C.2 Modelling and Simulation Methods at a Mesoscale

Similar to the Maitland case study (refer to Section B.2), the Weather Research and Forecasting (WRF) model was employed for the cooling potential analysis of the Dubbo Region at a mesoscale. In this model, four layers of two-way nested domains were created for the Dubbo Region. Outer domains had a coarser resolution while inner domains had a finer resolution. Outer domains served the role of providing dynamic boundary conditions for inner domains. The innermost domain, i.e. Domain 4 labelled d04 in Figure C-5, covered the majority of the Dubbo Region, with a resolution 500 m in the WRF model. The World Urban Database and Access Portal Tools (WUDAPT) were employed for the land cover data for the Dubbo Region, along with other datasets. The Local Climate Zone (LCZ) schema was utilised for classifying the surface structure (e.g. building and tree height, and their densities) and surface cover (e.g. pervious and impervious surface covers). Anthropogenic heat was included in the WRF model through a dynamic parameterisation schema. The actual value of anthropogenic heat at each grid point in the WRF model changed based on the real-time cooling load within buildings over time. Figure C-6 presents the land use and LCZ in the Dubbo Region, and Figure C-7 presents the peak anthropogenic heat from HVAC over different LCZs in the Dubbo Region.

The validation of the WRF model was conducted by comparing the simulation results with weather station data to ensure feasibility and accuracy. All available weather stations in the Dubbo Region from the Bureau of Meteorology (BOM) were used for validation, including the Dubbo airport weather station (-32.2206, 148.5753). Table C-1 outlines the comparison results between the weather station and simulation data of air temperature at 2 m, relative humidity at 2 m, and wind speed at 10 m during the two heatwave simulation periods.

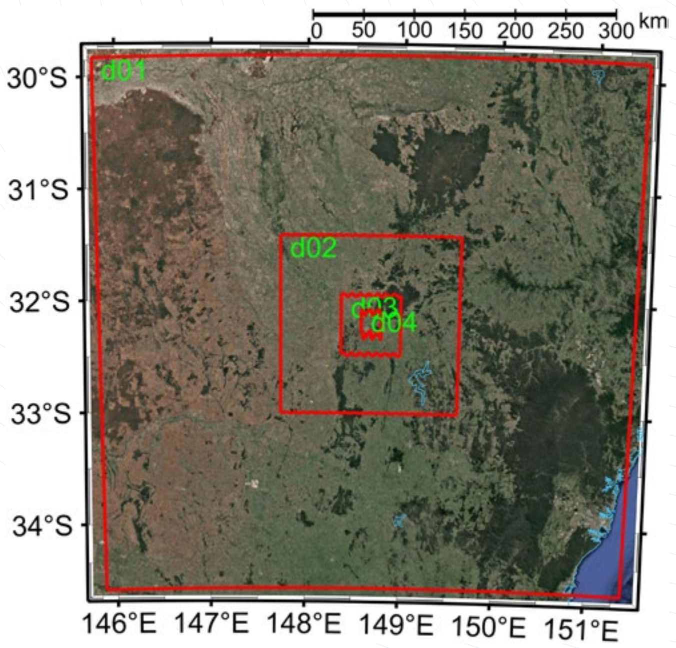

Figure C-5. Domains setting in WRF model, where d04 denotes Domain 4 covering a 48.5 km by 36.5 km area encompassing the majority of Maitland City. Domain 4 (d04) has a resolution 500 m in the WRF model.

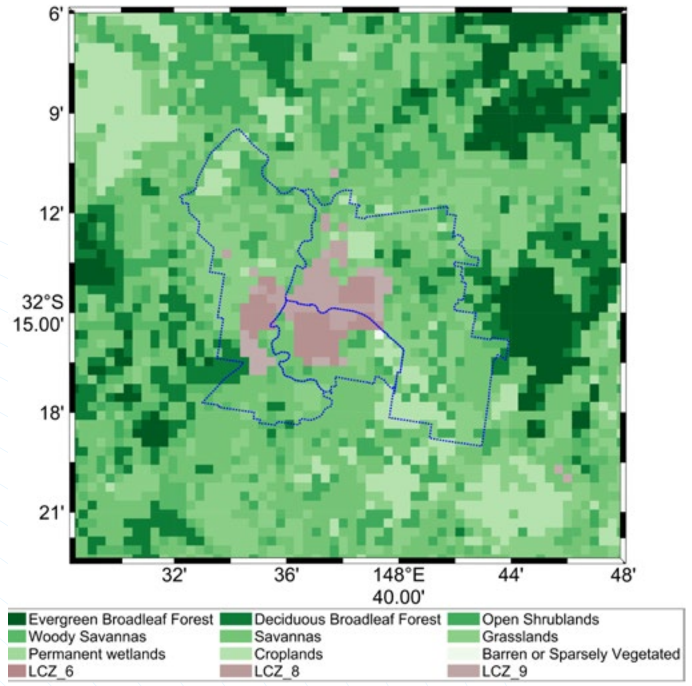

Figure C-6. The land use and LCZ in the Dubbo Region in the WRF model.

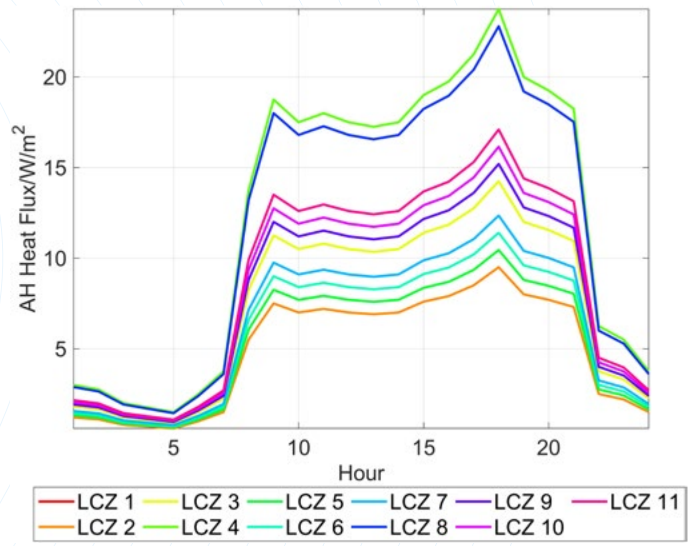

Figure C-7. The peak anthropogenic heat from HVAC over different LCZs in the Dubbo Region.

Table C-1. The comparison results between the weather station and simulation data of air temperature at 2 m, relative humidity at 2 m, and wind speed at 10 m during the two heatwave simulation periods. Where, ME denotes mean bias, FB denotes fractional bias, R denotes correlation coefficient, NMSE denotes normalised mean square error, and FAC2 denotes the fraction of simulation values within a fraction of two of weather station data.

Statistical Parameter	December 22nd, 2019, to January 8th, 2020			January 18th, 2020, to February 3rd, 2020		
	Temperature/ °C	Relative humidity/%	Wind speed/ m/s	Temperature/ °C	Relative humidity/%	Wind speed/ m/s
MB	0.692	2.713	-1.878	0.530	2.404	-2.067
FB	0.026	0.103	-0.393	0.024	0.083	-0.513
R	0.957	0.940	0.683	0.917	0.831	0.591
NMSE	0.000	0.000	0.001	0.000	0.000	0.001
FAC2	1.000	0.977	0.729	1.000	0.976	0.583

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C.3 Urban Heat Mitigation Strategies at a Mesoscale

Key mitigation strategies were applied to the Dubbo Region to understand the maximum cooling potential at the mesoscale. These mitigation strategies were similar to those applied to Maitland City (refer to Section B.3) and included cool materials with increased albedo for urban hard surfaces such as roads and roofs, increased greenery with broadleaf trees, increased greenery with water irrigation, and a combination of all these mitigation options (Table B-2), but they were tailored to the local urban context in the Dubbo Region.

Cool Materials

Cool materials were applied to urban hard surfaces including roads, impervious pavements, and roofs to reduce the shortwave radiation absorbed by the city, thereby achieving a cooling effect through a reduction in surface sensible heat. This mitigation strategy included increasing the albedo value from 0.3 to 0.8 for roofs and from 0.15 to 0.5 for roads and impervious pavements in the Dubbo Region. As a result, the overall average albedo of the urban grid in the model was increased from the 0.25 to 0.35 for the Dubbo Region (Figure C-8).

Greenery

Urban greenery comprises a mix of grass, shrubs and trees. This mitigation strategy focused on tree planting, which included replacing existing trees with broadleaf trees, and increasing trees coverage in the built area to 40% to understand the maximum cooling potential by enhancing urban greenery. Additionally, it also increased trees coverage in the southern and eastern suburban areas in the

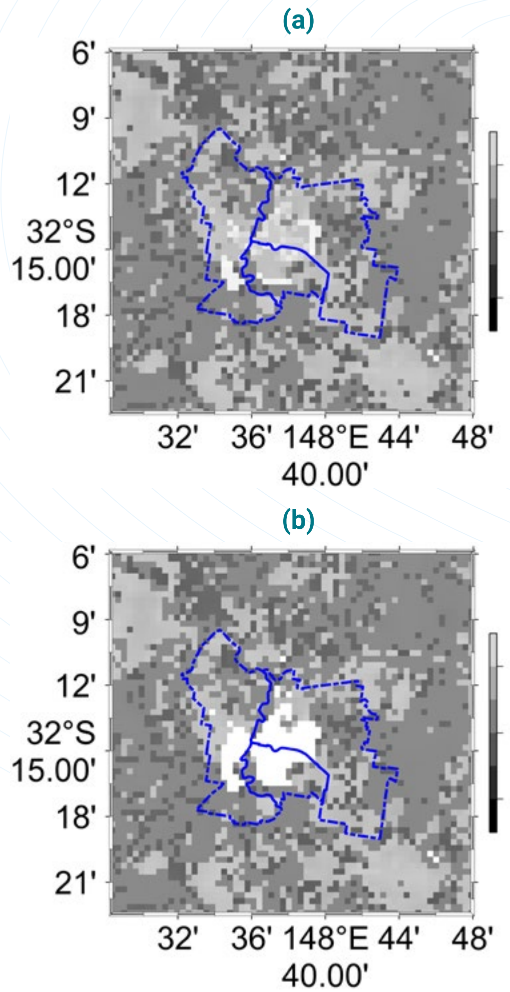


Figure C-8. The albedo values of urban hard surfaces: (a) base case and (b) cool materials applied to roads, impervious pavements, and roofs in the Dubbo Region.

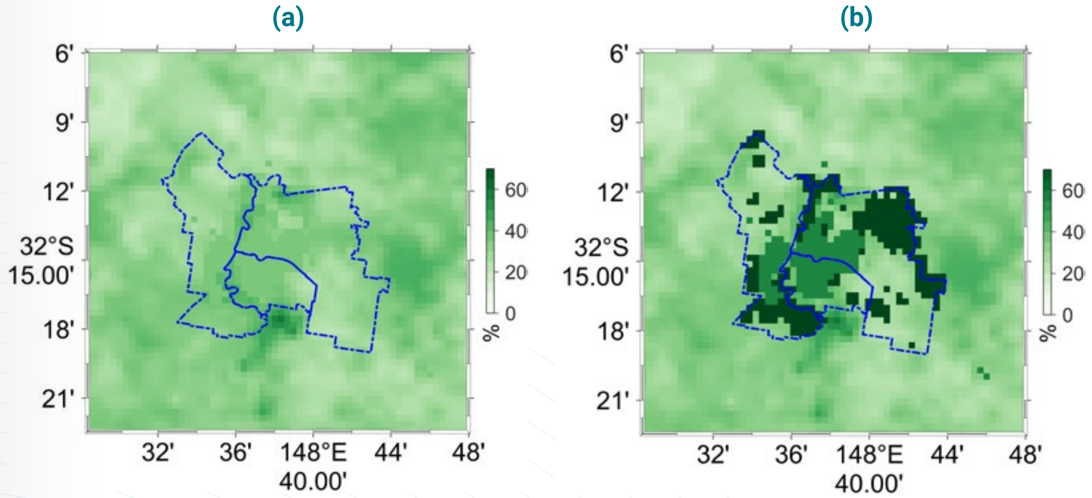


Figure C-9. The urban greenery fraction: (a) base case and (b) increased urban greenery in the Dubbo Region.

Dubbo Region to enhance cooling effects. Figure C-9 (a) and (b) show the existing and increased urban greenery coverage respectively in the Dubbo Region, while detailed parameters for urban greenery are provided in Appendix 1.

Greenery with Water Irrigation

Dynamic water irrigation was applied to urban greenery, considering the significant impact of water transpiration on urban greenery. This mitigation strategy monitors soil moisture levels and provides timely water irrigation to maintain optimal soil moisture for maximising transpiration. It increased the average soil moisture during the two heatwave periods by 0.1 m^3/m^3 on the top layer of the soil (0-10 cm) for the urban greenery area, including increased tree coverage. Figure C-10 (a) and (b) show the average soil moisture of the existing urban greenery coverage and increased urban greenery coverage respectively in the Dubbo Region.

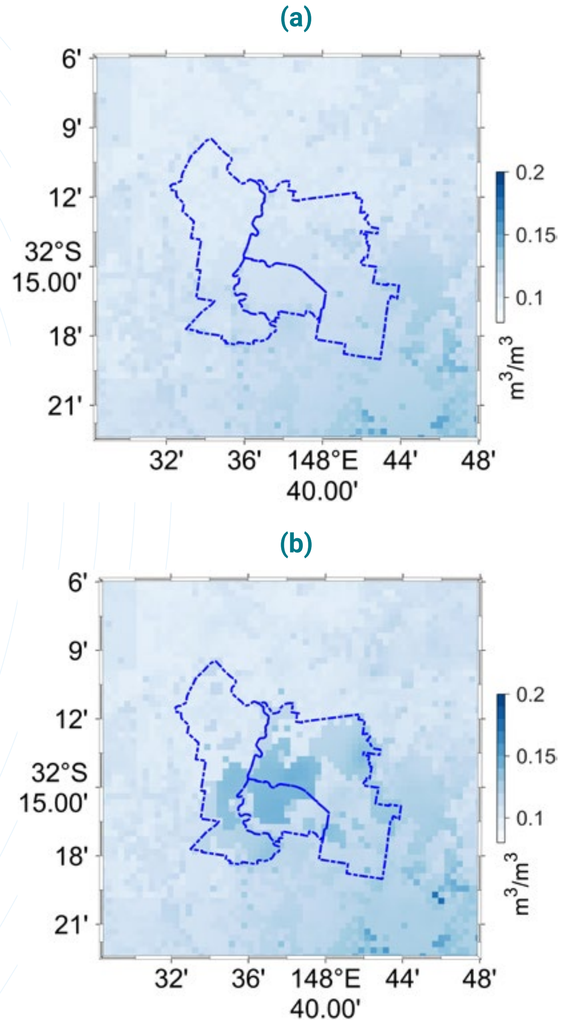


Figure C-10. The average soil moisture on the top layer of the soil (0-10 cm): (a) base case and (b) increased urban greenery coverage in the Dubbo Region.

Combination of Mitigation Options

A combination of all the above mitigation strategies was applied to the Dubbo Region to understand the maximum cooling potential across the entire area. This included the application of cool materials to roads, impervious pavements, and roofs, as well as increasing urban greenery with water irrigation.

C.4 Cooling Potential Analysis for Dubbo at a Mesoscale

C.4.1 Cooling Potential by Mitigation Strategies at a Mesoscale

The maximum daily cooling potential of the different mitigation strategies (as described in Section C.3) is shown in Figure C-11. Increasing urban greenery with water irrigation significantly contributed to air temperature reduction during both daytime and nighttime in the Dubbo Region, demonstrating higher cooling benefits compared to urban greenery without water irrigation. Additionally, the application of cool materials primarily contributed to air temperature reduction during the daytime. Notably, the combination of all mitigation options achieved the highest cooling effect, resulting in air temperature reductions of up to 2.0 °C. These results relate to the built-up area within the Dubbo Region, rather than the entire area.

Figure C-12 and Figure C-13 show the maximum cooling effect hourly during the first and second heatwave periods respectively. The cooling effect from the application of cool materials remained stable and consistent throughout the first heatwave period. During the second heatwave period, there were significant daily variations in the maximum temperature reduction for all mitigation strategies, especially for the strategy of increasing urban greenery with water irrigation. These variations were driven by significant changes in local weather conditions. This demonstrates that the cooling effect of increasing urban greenery with water irrigation was more sensitive to daily weather variations.

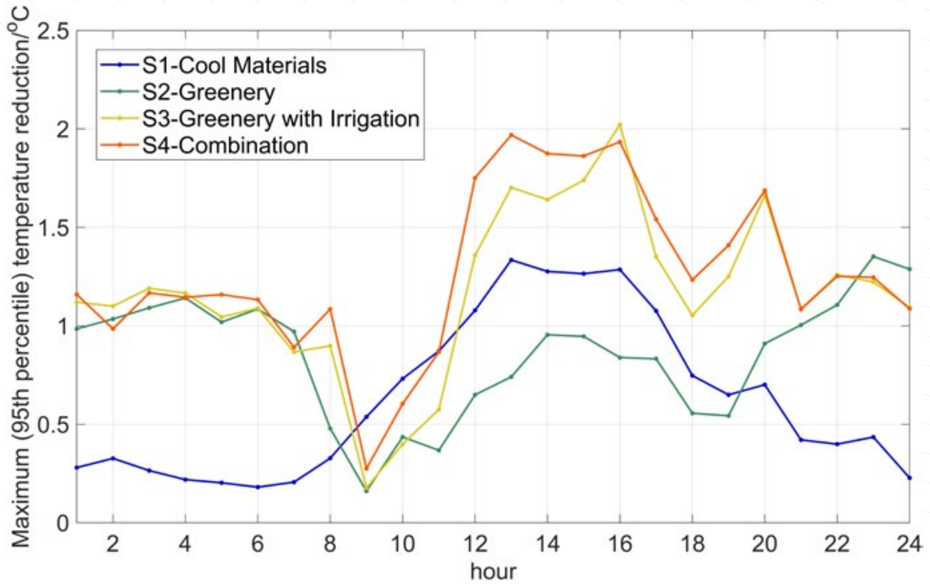


Figure C-11. The maximum daily cooling potential of the different mitigation strategies (as described in Section B.3), which refers to the 95th percentile of maximum daily air temperature reductions during the heatwave periods.

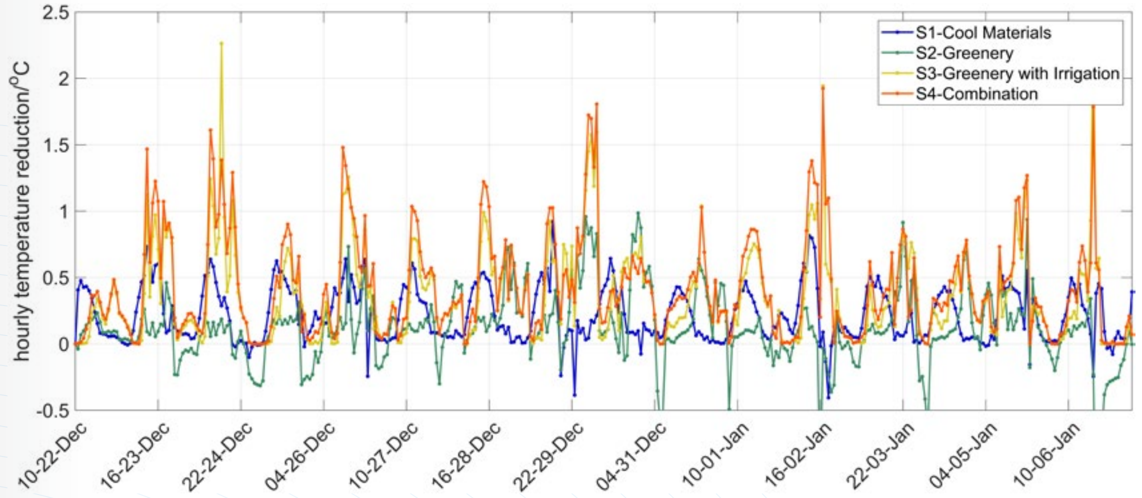


Figure C-12. The maximum air temperature reduction hourly during the first heatwave period.

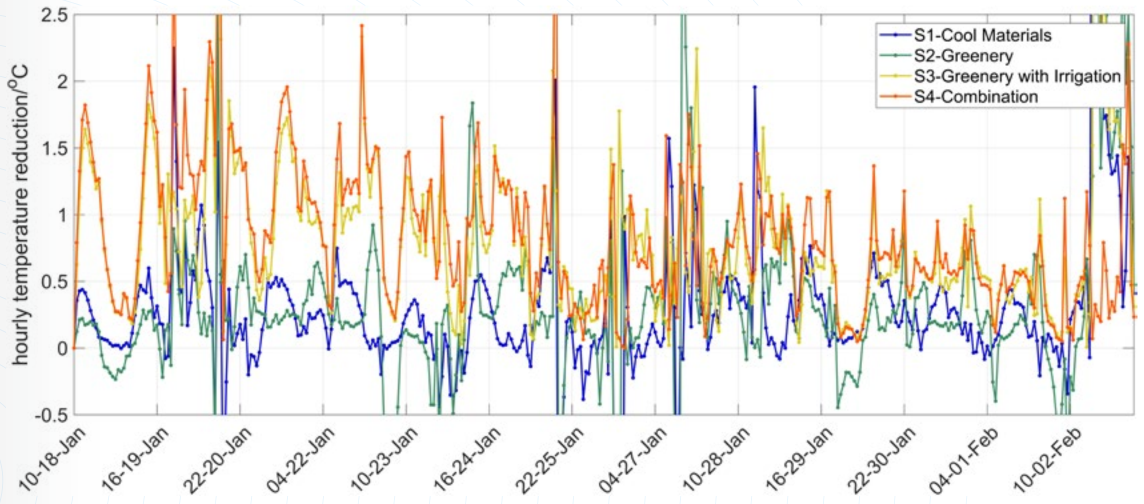
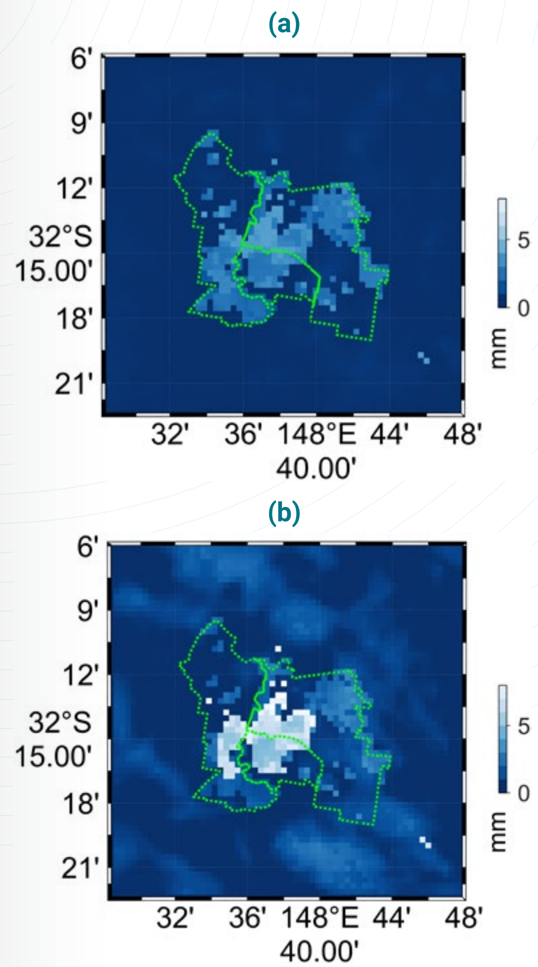


Figure C-13. The maximum air temperature reduction hourly during the second heatwave period.



C.4.2 Water Consumption Resulting from Water Irrigation for Urban Greenery

Daily water consumption from urban greenery with irrigation was predicted based on the cumulative changes in accumulated evapotranspiration. The average daily water irrigation volume for urban greenery in the built-up area in the Dubbo Region ranged from 2 mm to 8 mm over the two heatwave periods (Figure C-14). Specially, the estimated total daily water consumption ranged from 470 m³/km² to 1175 m³/km², depending on weather conditions.

Figure C-14. The estimated average daily water irrigation volume for urban greenery in the built-up area in the Dubbo Region during: (1) the first heave period and (2) the second heatwave period.

C.4.3 Reduction in Cooling Degree Days and Cooling Loads

Similar to the Maitland case study, Cooling Degree Days (CDD) were employed to assess the severity of urban heat and forecast cooling loads in buildings for the Dubbo case study. CDD measures the accumulation of degrees and duration of time where the outdoor average air temperature exceeds a defined base air temperature, indicating the need for cooling. A base temperature of 23 °C was defined in this project.

The mitigation strategies at the mesoscale, described in Section C.3, have demonstrated the potential to achieve significant reductions in Cooling Degree Days (CDD) in the Dubbo Region, as shown in Figure C-15. This reduction in CDD corresponds to energy savings in cooling loads for buildings. Figure C-16 estimates the decrease in cooling loads for a representative house in the Dubbo Region resulting from the implementation of these mitigation strategies.

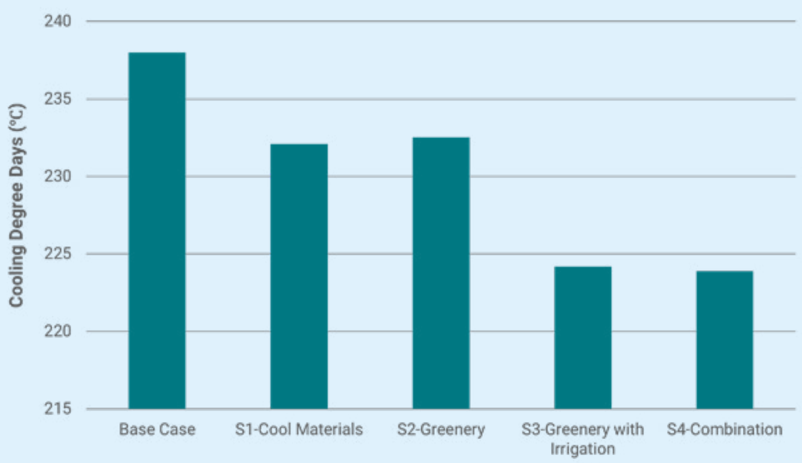


Figure C-15. The estimated reduction in CDD in the Dubbo Region resulting from the implementation of the mitigation strategies at the mesoscale.

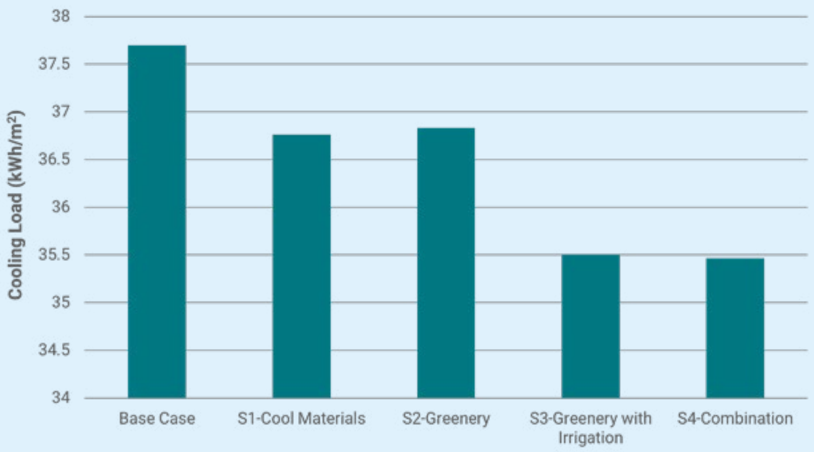


Figure C-16. The estimated decrease in cooling loads for a representative house in the Dubbo Region resulting from the implementation of the mitigation strategies at the mesoscale.

C.5 Cooling Potential for Dubbo at a Microscale

C.5.1 Modelling and Simulation Methods at a Microscale

This project also conducted a microscale cooling potential analysis for case study precincts in the Dubbo Region, specifically Southlakes and South Dubbo. The computational Fluid Dynamic (CFD) based model, ENVI-met, was employed for the microscale cooling potential analysis. Additionally, the validation of the CFD model was conducted by comparing simulation results with field measurement results in the case study precincts.

Key Parameters

January 30, 2020, during the second heatwave period (refer to Section C.1), was selected for the microscale CFD model. The day was characterised by hot, sunny conditions with a maximum temperature of 40.6 °C. The daily average wind speed was 5.2 m/s, predominantly from the south, east, and southeast. An alternative weed speed of 2.4 m/s was also applied to investigate the impact of varying wind speeds on cooling effects. The simulation time was set from 7:00 to 24:00 to analyse the cooling potential, covering both daytime and evening periods. Heatmaps were generated for 14:00 to show air and surface temperature distributions across the case study precincts in the Dubbo Region. Air temperatures at pedestrian level (1.5 m) and surface temperatures on the ground were used for a comparative analysis of the cooling potential.

The parameters for urban surfaces and building materials in the Dubbo case study precincts were same as those applied in the Maitland case study precincts (see Table B-3). However, the properties of trees for the Dubbo case study precincts differed slightly from those in the Maitland case study precincts (refer to Table C-2), as they were tailored to the local urban context. All these parameters were validated prior to the simulations. Cool materials used for cool roofs, cool pavements, and cool roads are the existing cool materials commonly used, rather than advanced super cool materials currently under development.

Table C-2. The properties of trees for the Dubbo case study precincts.

Sizes	Tree Height (m)	Canopy Width (m)
Small	5.79	4.91 x 4.84
Medium	11.02	7.76 x 7.92
Large	17.25	13.28 x 13.51

Model Validation

An on-site measurement was conducted for model validation. It compared air temperatures, relative humidity, wind speeds and directions, and solar radiation from simulations to the measurement results in the Dubbo case study precincts. The validation results indicated that the simulation results closely matched the measurement results (Figure C-17).

Sensor Data

Sensors for monitoring air temperatures and humidities were installed at the case study precincts in the Dubbo Region. These sensors were used for both model validation and ongoing monitoring of outdoor thermal environments, as well as future changes in outdoor thermal comfort resulting from the implementation of mitigation strategies. Figure C-18 presents sensor data of air temperatures collected on 29 January 2024 from the case study precincts: Southlakes and South Dubbo.

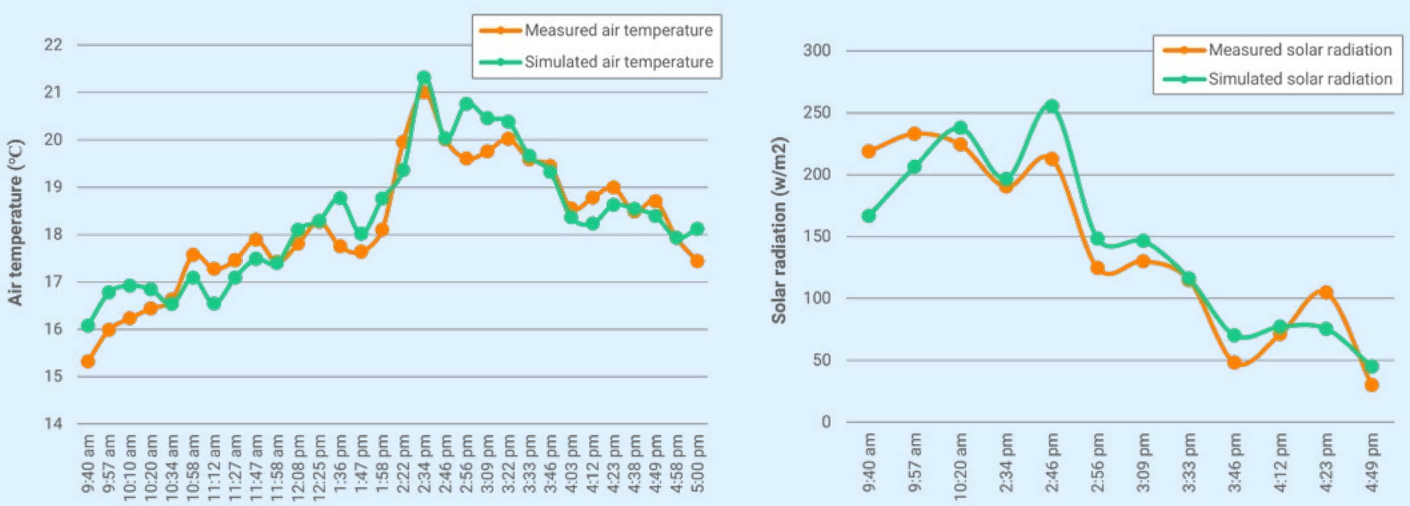


Figure C-17. Model validation results indicated that the simulation results closely matched the measurement results.

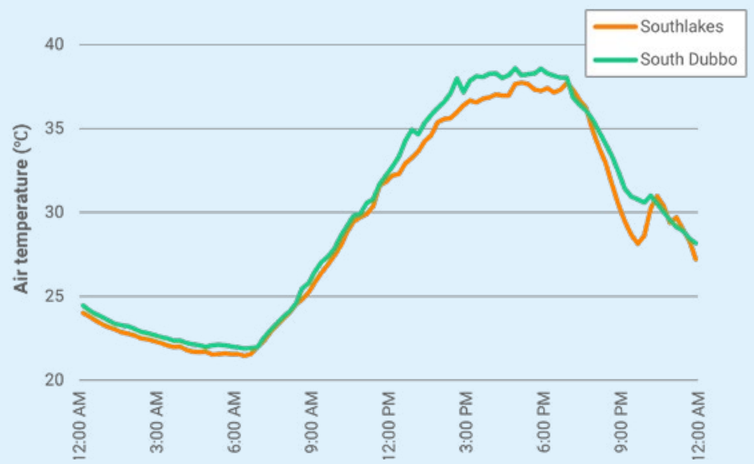


Figure C-18. Sensor data of air temperatures collected on 29 January from the case study precincts: Southlakes and South Dubbo.

C.5.2 Urban Heat Mitigation Strategies at a Microscale

In alignment with the urban heat mitigations strategies at a mesoscale (refer to Section C.3), mitigation strategies for the case study precincts in Dubbo were co-designed by the project team and the Dubbo Regional Council. These mitigation strategies were developed based on the specific local built environment characteristics and heat vulnerability challenges identified to understand the maximum cooling potential. Additionally, subdivision scenarios for the new development area in the Southlakes case study precinct were further investigated along with mitigation strategies to understand the impact of building density changes and to inform local planning controls.

Table C-3 lists the mitigation strategies applied to Southlakes and South Dubbo, as well as the subdivision scenarios planned for the new development of Southlakes. These mitigation strategies encompass both public and private realms. In-depth analyses were conducted for Soutlakes, including changes in subdivisions by increasing building density and applying individual and combined mitigation strategies.

Table C-3. The mitigations strategies and subdivision scenarios applied to the case study precincts in Dubbo.

CASE STUDY PRECINCTS	INDIVIDUAL AND COMBINED MITIGATION STRATEGIES AND SUBDIVISION SCENARIOS	
Southlakes	Base Case	Predominantly 600 m² lots
	Mitigation Strategies	Increased public and private greenery
		Cool materials for all roads, footpaths and private hard surfaces
		Cool roofs for all buildings
		Combination of increased greenery, cool pavements, and cool roofs applied with additional water misting for hotspots and outdoor shading for public open spaces
	Subdivision Scenarios	Subdivision of 1000 m² lots
		Subdivision of 300 m² lots
		Subdivision of 300 m² lots plus increased public parks
		Subdivision of 300 m² lots with a combination of increased greenery, cool pavements, and cool roofs applied with additional water misting for hotspots and outdoor shading for public open spaces, plus increased public parks
South Dubbo	Base case	
	Combination of increased greenery, cool pavements, and cool roofs applied with additional water misting for hotspots and outdoor shading for public open spaces	

C.5.3 Cooling Potential of Mitigation Strategies in Southlakes

Heat Vulnerability Challenges and Built Environment Characteristics of Southlakes

Dubbo Regional Council identified Southlakes as a priority area of investigation for the NaHVO's Phase 1 pilot due to its representativeness of the future residential development typology in Dubbo. In other words, understanding and reducing heat vulnerability in this precinct can inform future heat-resilient development across Greater Dubbo. Southlakes comprises detached one and two-storey houses on mostly smaller lots, which leaves few opportunities for private green space and tree canopy coverage. Towards the southern boundary of the precinct there are larger detached homes on substantially sized lots, which provides larger areas of pervious surfaces but with limited private tree canopy coverage. The south-east of Southlakes is currently under construction, but the simulations included built environment features within this area that are aligned with these two residential types as per the precinct's masterplan.

Based on the NaHVO Index datasets, Southlakes has a higher overall proportion of pervious surfaces compared to the other precincts in the NaHVO Phase 1 pilot, which results in lower surface temperatures, especially when irrigated (shown in purple and blue in Figure C-19). Despite this, Southlakes has the lowest overall tree canopy coverage, which is evident through the unshaded roads with high surface temperatures (shown in red and yellow in Figure C-19). This is likely a symptom of being a new residential development where street trees are not well established yet, and resident preferences. Southlakes also has the highest proportion of light-coloured roofs, which can be seen in light blue in Figure C-19. Based on the NaHVO Index results, Southlakes presented predominantly high thermal, energy and health heat vulnerability index values throughout the Phase 1 study period. The detailed built environment characteristics and heat vulnerability challenges for Southlakes are provided in Table C-4.

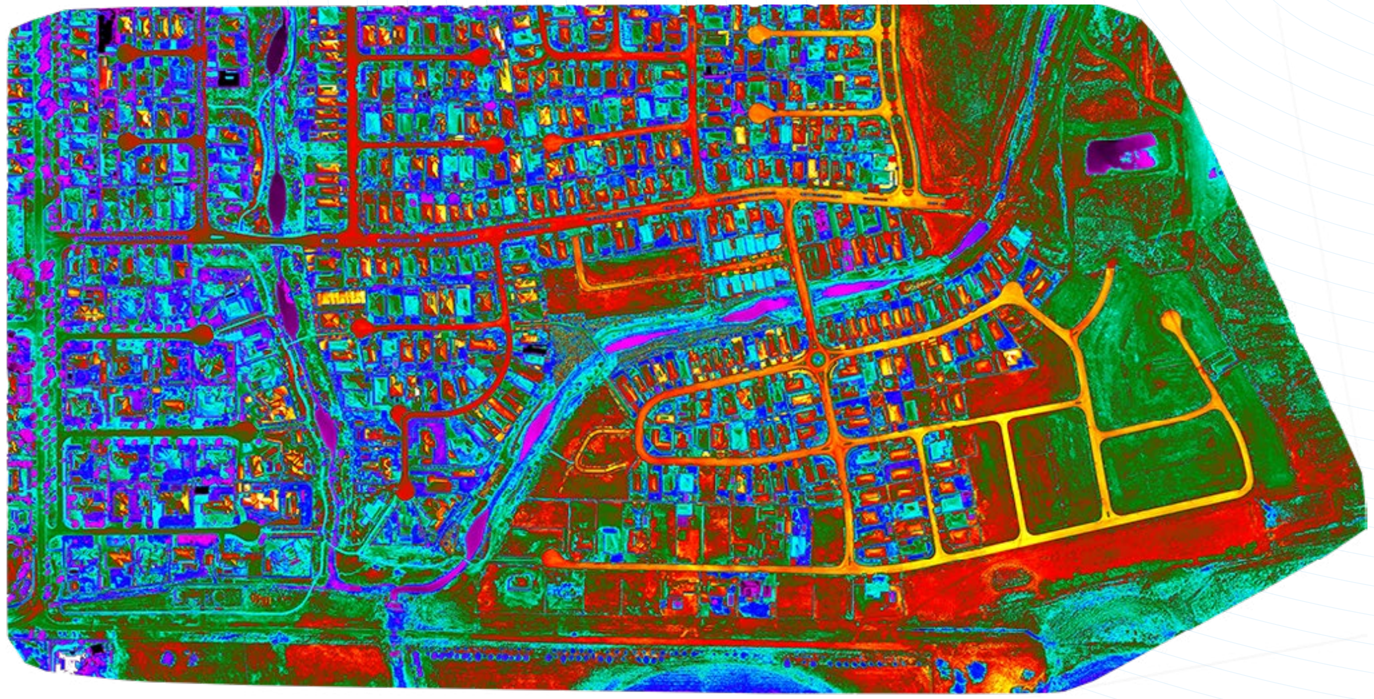


Figure C-19. Surface temperature thermal imagery of Southlakes taken between 11:44 am and 3:10 pm on 12 November 2023.

View of Southlakes via drone aerial photography (UNSW High Performance Architecture).

Southlakes represents the typical residential development typology for future growth in Dubbo and as such, it was the major focus of the heat mitigation strategies for Dubbo. This section presents the cooling potential results for the five heat mitigation and four subdivision scenarios for Southlakes outlined in Table C-3. These results are presented as reductions in air and surface temperature for a representative hot summer's day (including the evening) during the NaHVO's Phase 1 study period (see C.5.1), as compared to the existing conditions (base case) of Southlakes.

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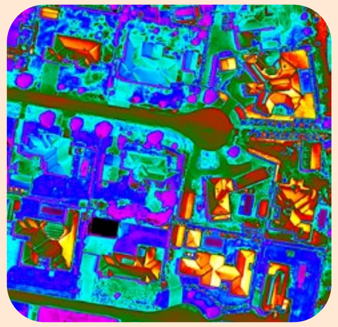
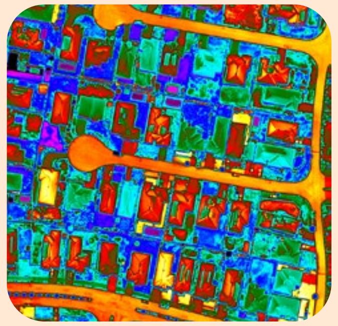
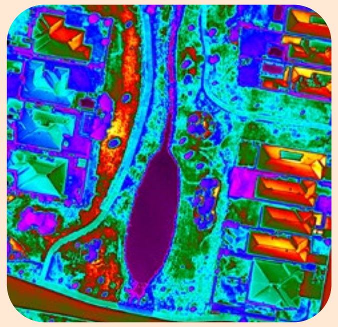
- Base Case -

Figure C-20 shows the modelled existing conditions of Southlakes including 3D building objects and trees, road and footpath networks, and water bodies. This was generated from a wide range of data sources from Dubbo Regional Council, open-source datasets, and satellite imagery (see Report D for more detail). This model of Southlakes was used to simulate a base case scenario, which formed the basis to compare the defined cooling intervention and subdivision scenarios against. As mentioned in Section C.5.1, this base case model was validated with on-site measurements for air temperature, relative humidity, wind speed and direction, and solar radiation to ensure the simulated results were as close as possible to reality.

Table C-4. Built environment characteristics and heat vulnerability challenges in Southlakes.

THERMAL IMAGERY	AERIAL IMAGERY	STREETSCAPE	BUILT ENVIRONMENT CHARACTERISTICS	HEAT VULNERABILITY CHALLENGES
			» Low-rise detached residential buildings with a sparse layout. » Large areas of private pervious surfaces with low tree canopy coverage. » Narrow roads with low street tree canopy coverage. » Moderate proportion of dark-coloured roofs.	» Exposed private open space due to limited private tree canopy. » Exposed hard surfaces with high surface temperatures along streets from limited tree canopy. » Narrow roads limit the opportunities for raingardens and outdoor shading. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Low-rise detached residential buildings with a compact layout. » Small to moderate areas of pervious and impervious private open space with limited trees. » Narrow roads with low street tree canopy coverage. » Moderate to high proportion of dark-coloured roofs.	» Exposed private open space due to limited private tree canopy. » Exposed hard surfaces with high surface temperatures along streets from limited tree canopy. » Narrow roads limit the opportunities for raingardens and outdoor shading. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Linear green open space with small water bodies and low to moderate tree canopy coverage.	» Areas of unirrigated and unshaded grass have higher surface temperatures. » Small water bodies can only provide a limited cooling effect for its immediate surroundings.

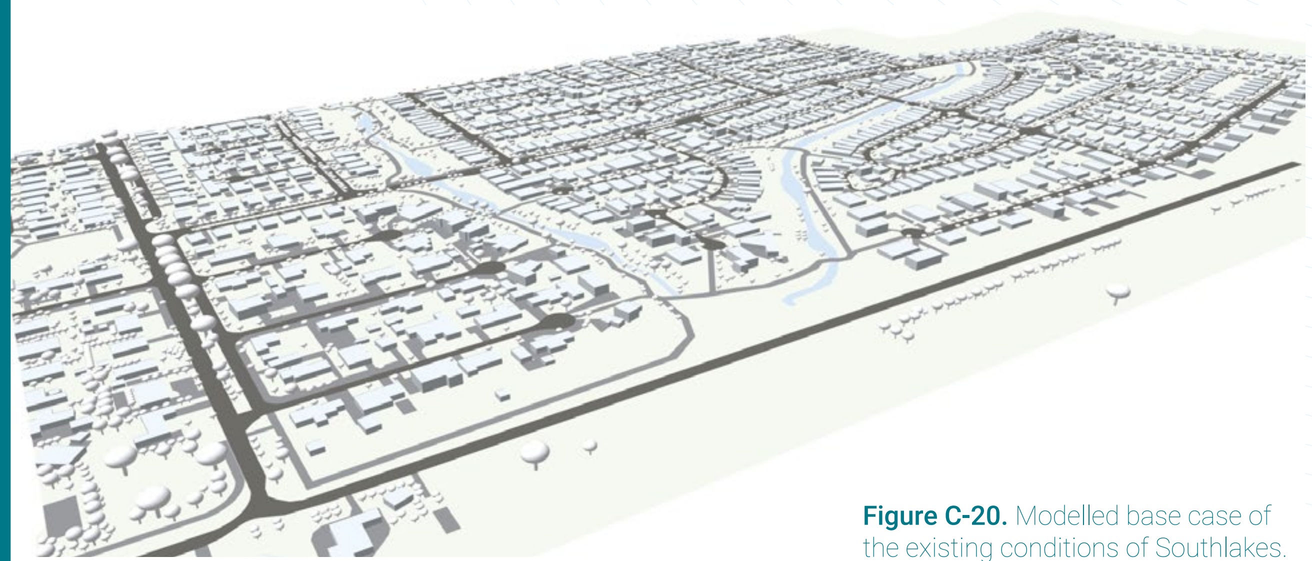


Figure C-20. Modelled base case of the existing conditions of Southlakes.

Figure C-21. Simulated air temperature distribution of the existing base case conditions of Southlakes at 2pm.

Figure C-21 presents the air temperature distribution of the simulated base case at 2pm for the Southlakes case study precinct. This shows that the air temperature was evenly distributed across the precinct. However, the air temperature was generally lower in the larger lot residential areas of the precinct to the south and along the linear green open spaces with small water bodies. These areas were approximately 2 to 3 °C less than the more compact residential areas of Southlakes (Figure C-21).

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- Cooling Potential of Increasing Public and Private Greenery -

The existing greenery conditions of Southlakes offered opportunities to increase the proportion of public and private greenery across the precinct. This cooling intervention scenario increased the total tree canopy coverage of Southlakes by 2.8%. Figure C-22 shows the location and scale of these additional trees, which was primarily in public areas to the north due to limited opportunities for private greenery in the compact residential areas. While a more extensive tree strategy was initially simulated in the southern areas of this precinct, this was found to result in a potential heat trap due to the interactions between the prevailing wind conditions, street orientation, and tree density on high temperature days. These additional trees were based on the defined tree properties shown in Table C-2, and the planting strategy was informed by Dubbo Regional Council's Street Tree Masterplan[58] and Toolkit[59].

Figure C-23 presents the air and surface temperature reduction distributions at 2pm and 9pm for increasing public and private greenery in Southlakes. During the day, significant air and surface temperature reductions were achieved but limited to the northern areas of Southlakes with lower wind speeds. During the evening, there was still a cooling benefit in air and surface temperature from increasing public and private greenery across Southlakes, but the impact is relatively limited (Figure C-23). Figure C-24 shows the hourly maximum air and surface temperature reductions possible from increasing public and private greenery in Southlakes. A maximum air temperature reduction of 1.4 °C was achieved at 11am, and a maximum surface temperature of more than 13 °C was achieved between 12pm and 1pm.

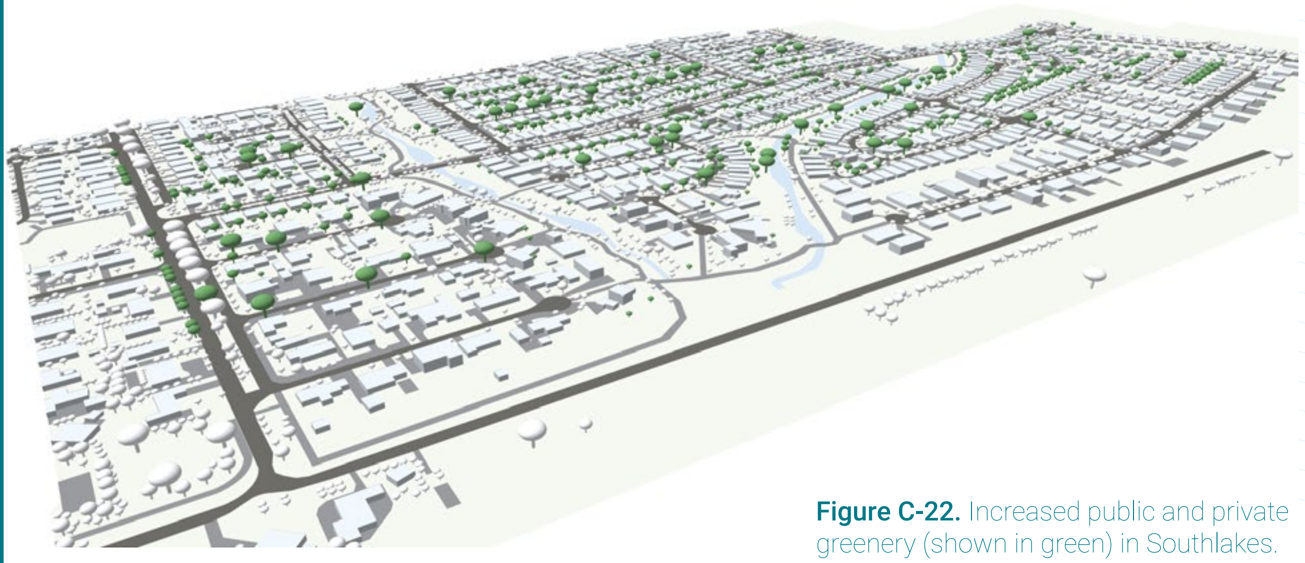

Figure C-22. Increased public and private greenery (shown in green) in Southlakes.

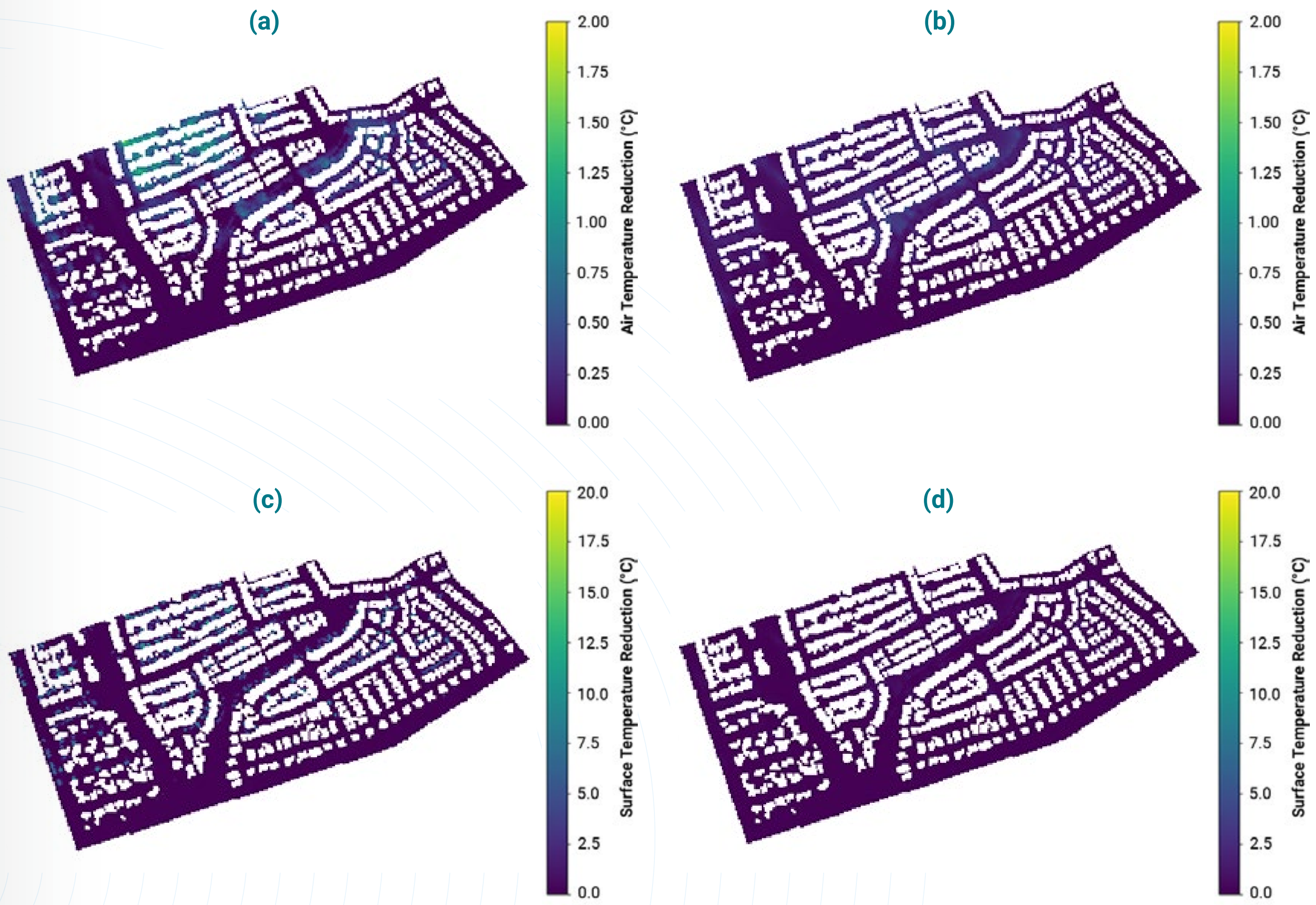

Figure C-23. Air temperature reduction distributions at (a) 2pm and (b) 9pm; and surface temperature reduction distributions at (c) 2pm and (d) 9pm; from increasing public and private greenery across Southlakes.

Figure C-24. Hourly maximum (a) air temperature and (b) surface temperature reductions from increasing public and private greenery across Southlakes.

- Cooling Potential of Cool Materials for All Roads, Footpaths and Private Hard Surfaces -

While Southlakes may have the highest proportion of pervious surfaces compared to the other NaHVO Phase 1 precincts, it still has a substantial road network to support the high proportion of private motor vehicles in Dubbo. As outlined previously, these asphalt roads, combined with concrete footpaths and private hard surfaces, can exacerbate local urban overheating. In addition to shading these hard surfaces with increased greenery, another effective cooling intervention is to change the material properties of these hard surfaces to increase their albedo and emissivity, which transforms them into cool materials. This cooling intervention scenario represents the maximum cooling potential of changing all roads, footpaths and private hard surfaces in Southlakes to be cool materials (Figure C-25) based on the cool road and pavement material properties outlined in Table B-3.

Figure B-26 shows the air and surface temperature reduction distributions at 2pm from applying cool materials for all roads, footpaths and private hard surfaces in Southlakes, and Figure C-27 shows its hourly maximum air and surface temperature reductions throughout the selected simulation day. Naturally, the cooling impact of applying these cool materials was higher on the wider unshaded streets and during the middle of the day with high solar radiation. These air and surface temperature reductions were more prominent in the northern areas of Southlakes due to the interactions between the prevailing wind conditions and the precinct's built form. The maximum air and surface temperature reductions of this scenario were approximately 0.7 °C and 7.2 °C respectively at 1pm (Figure C-27). As Southlakes has a high proportion of pervious surfaces, it is worth noting that in inner-city and dense urban contexts with higher proportions of hard surfaces, the cooling benefit of applying cool materials for all hard surfaces will be significantly greater. The cooling impact of the cool materials during the evening was very minor as the effectiveness of cool roads, pavements, and other hard surfaces is generally determined by its ability to reflect direct solar radiation.

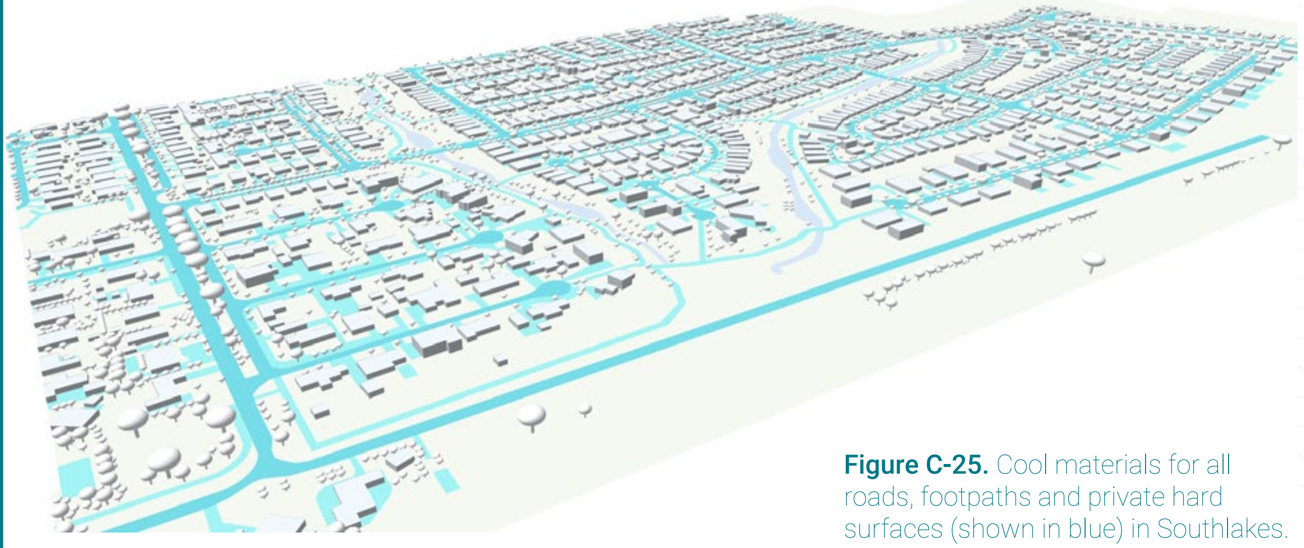

Figure C-25. Cool materials for all roads, footpaths and private hard surfaces (shown in blue) in Southlakes.

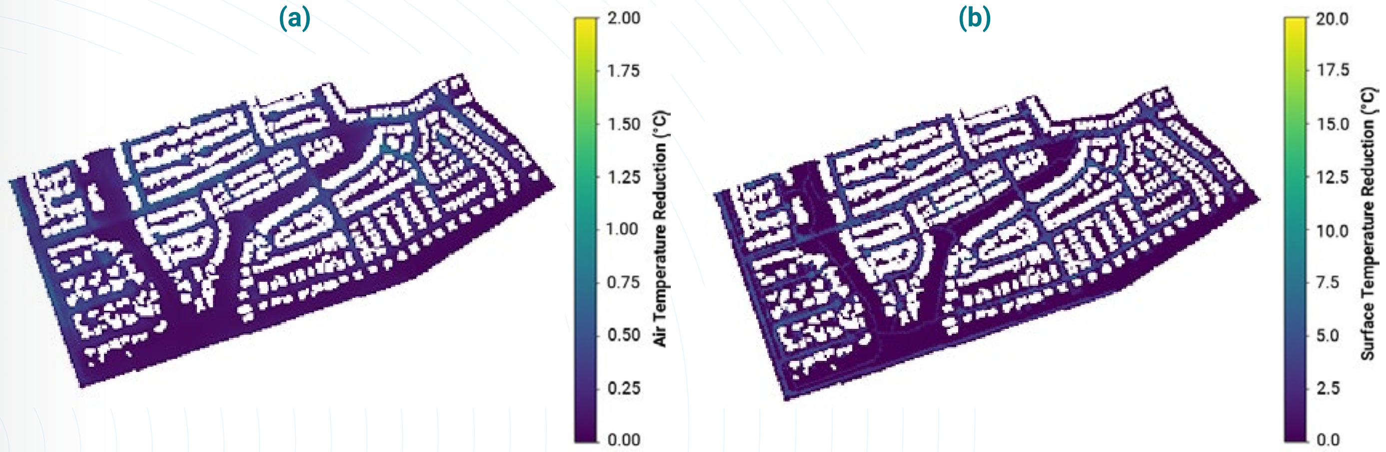

Figure C-26. (a) Air temperature and (b) surface temperature reduction distributions at 2pm from applying cool materials to all roads, footpaths and private hard surfaces in Southlakes.

Figure C-27. Hourly maximum (a) air temperature and (b) surface temperature reductions from applying cool materials to all roads, footpaths and private hard surfaces in Southlakes.

- Cooling Potential of Cool Roofs for All Buildings -

Although Southlakes has a higher proportion of light-coloured roofs, there are still many dwellings with dark roofs, which leads to high surface temperatures during extreme heat conditions. Like the previous scenario, changing the material properties of these roofs to be cool roofs can be an effective cooling intervention strategy, especially for the indoor thermal environment and subsequent cooling energy savings. This cooling intervention scenario represents the maximum cooling potential of changing all roofs to be cool materials (Figure C-28) based on the cool roof material properties outlined in Table B-3.

Figure C-29 and Figure C-30 show that the air temperature reductions from having all buildings in Southlakes with cool roofs was minor. The reasons for this are (1) that the air temperature reductions were for outdoor pedestrian-level air temperature, which is well below the roof level of the one and two-storey dwellings in Southlakes, and (2) there is a higher proportion of existing light-coloured roofs in Southlakes. It is worth emphasising that while cool roofs can have a minor cooling impact on outdoor pedestrian-level air temperature in this low-density residential context, their cooling impact on the indoor thermal environment and cooling energy savings is far greater.

Figure C-28. Cool roofs for all buildings (shown in yellow) in Southlakes.

Existing dark roofs of Southlakes (Nearmap).

Figure C-29. Air temperature reduction distribution at 2pm from applying cool roofs to all buildings in Southlakes.

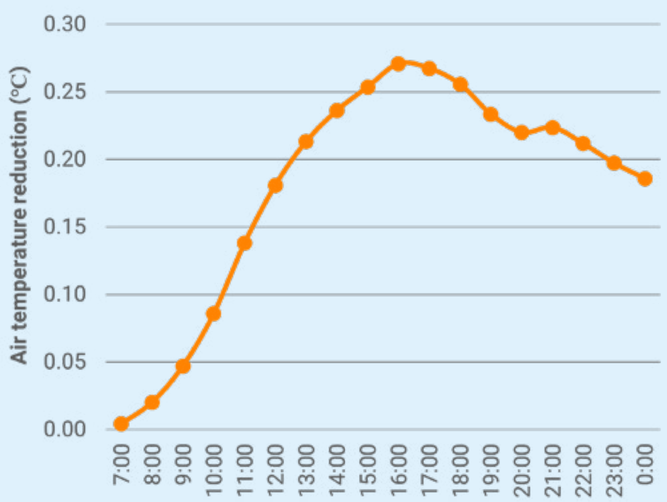

Figure C-30. Hourly maximum air temperature reductions from applying cool roofs to all buildings in Southlakes.

- Cooling Potential of a Combination of All Interventions Including Water Misting and Outdoor Shading -

This cooling intervention scenario for Southlakes represents the maximum cooling potential from a combination of mitigation scenarios. This included the increased public and private greenery and cool materials to all roofs, roads, pavements, and private hard surfaces from the previous scenarios (Figure C-31). This combined scenario also included the addition of outdoor shading and water misting located based on existing hot spots throughout Southlakes. This cooling intervention scenario therefore shows the maximum possible cooling impact for Southlakes without altering its existing built form, scale, and character.

Figure C-32 shows the air and surface temperature reduction distributions at 2pm from this combined mitigation scenario. These heatmaps show significant air and surface temperature cooling benefits. They also show the higher localised cooling benefits from the water misting and outdoor shading that were placed in existing hot spot areas throughout Southlakes. Like the previous scenarios, the maximum cooling impact of this combination of mitigation strategies occurred during the middle of the day. Maximum air temperature reductions above 1.6 °C were achieved between 11am to 1pm, and maximum surface temperature reductions above 12 °C were achieved between 12pm and 2pm (Figure C-33). There was also a minor but stable cooling benefit throughout the evening for both air and surface temperatures. This combination of mitigation scenarios for Southlakes reduced the NaHVO Index thermal heat vulnerability value from 9 to 7.

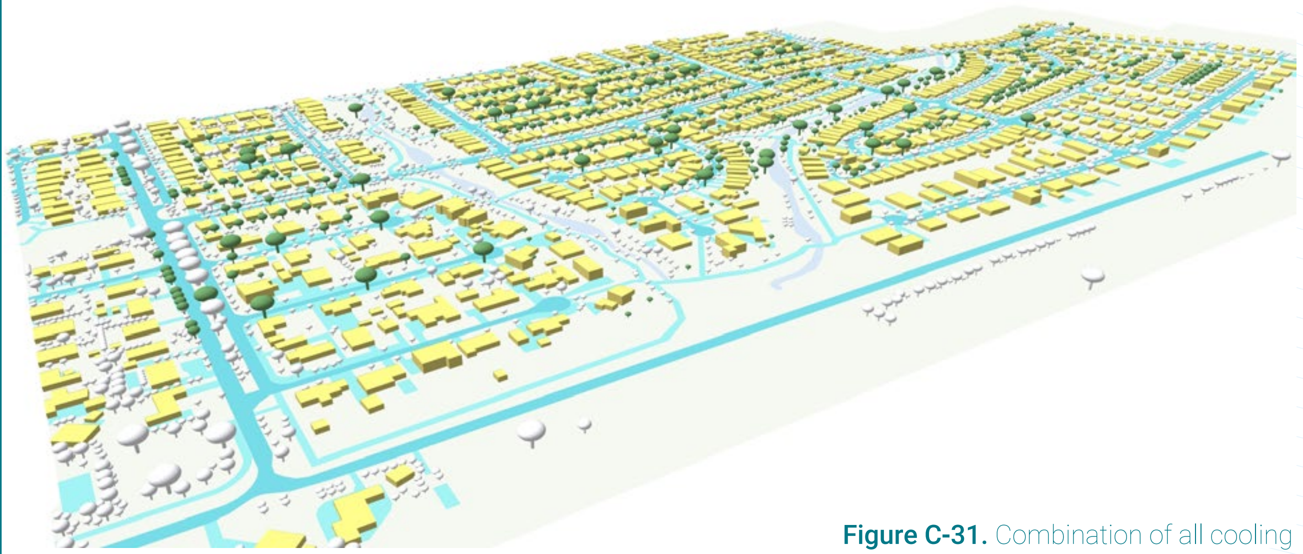

Figure C-31. Combination of all cooling interventions in Southlakes (coloured as per previous scenarios).

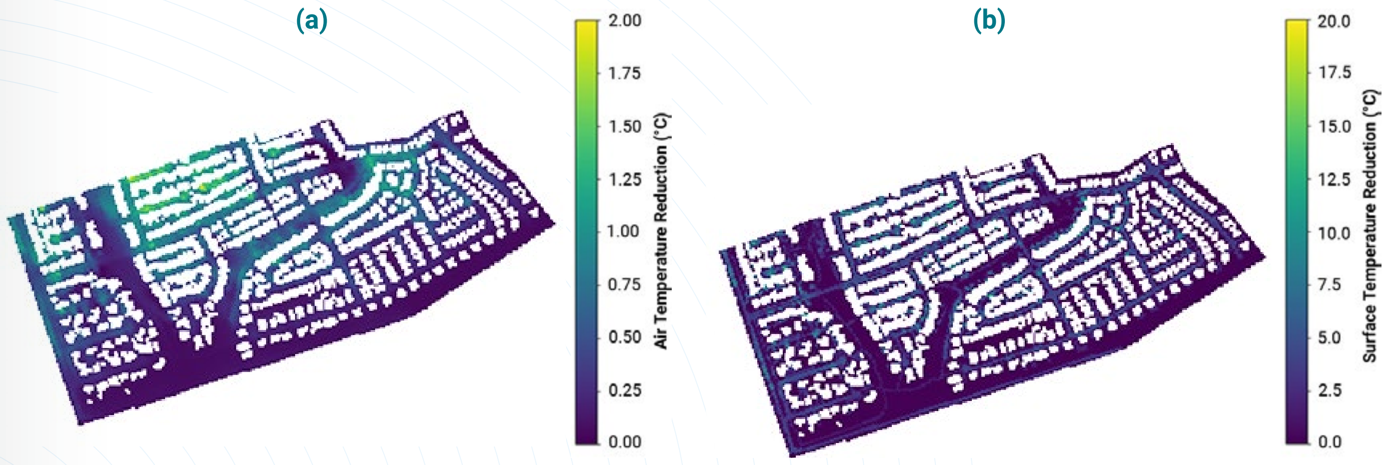

Figure C-32. (a) Air and (b) surface temperature reduction distributions at (a) 2pm from a combination of all mitigation strategies including water misting and outdoor shading in Southlakes.

Figure C-33. Hourly maximum (a) air temperature and (b) surface temperature reductions from a combination of all mitigation strategies including water misting and outdoor shading in Southlakes.

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- Comparative Analysis of Mitigation Strategies for Southlakes -

Figure C-34 presents a comparison of all cooling intervention strategies for Southlakes, showing both maximum and average hourly air and surface temperature reductions. At all times of the day, a combination of mitigation scenarios produced the greatest cooling benefit for Southlakes. These results reinforce the need for holistic and comprehensive measures to address heat vulnerability at the precinct scale, and not relying on a single cooling intervention. While the maximum cooling potential for the increased greenery scenario was higher than the cool materials scenario, it was less effective during the middle of the day on high temperature days, which resulted in a lower average precinct-wide cooling potential for Southlakes (Figure C-34). This is because extreme temperatures can affect the typical functioning of trees in certain urban contexts, thereby reducing their heat mitigation potential. It is worth emphasising again that the effectiveness of the cool materials scenario was limited by the lower proportion of hard surfaces in Southlakes' residential development typology compared to more dense urban contexts. The cool roof scenario was not included in this comparison due to its limited effectiveness in reducing outdoor pedestrian-level air temperature in this context, but cool roofs remain an important cooling intervention strategy to reduce indoor air temperatures and cooling energy demand during extreme heat events.

Figure C-34. Comparison of mitigation strategies for Southlakes showing hourly (a) maximum and (b) average air temperature reductions, and hourly (c) maximum and (d) average surface temperature reductions.

- Subdivision Scenario: All 1,000 m² Lots -

The first subdivision scenario for Southlakes involved changing the existing lot sizes to be approximately 1,000 m² (Figure C-35). The existing lot sizes in Southlakes are predominantly 600 m² with some larger 2,000 m² lots, which means that there was an overall decrease in housing density for this scenario. The detached housing typology, road network, tree canopy coverage, and proportion of dark roofs of the existing context in Southlakes were kept the same for this scenario. This was to ensure a fair comparison with the base case scenario to investigate whether reducing housing density, and therefore the proportion of hard surfaces, would have a cooling impact for Southlakes.

Figure C-36 shows that the air and surface temperature reduction distributions from changing all lot sizes in Southlakes to be 1,000 m² is minor. This cooling potential was also limited to north and north-east areas of the precinct, which is likely due to the changed wind distribution from decreasing density in these areas. Figure C-37 shows that the maximum air and surface temperature reductions from this scenario are 0.8 °C at 1pm and 8.2 °C at 3pm respectively. This indicates that while there was a potential cooling benefit from changing all lot sizes in Southlakes to 1,000 m², the magnitude of this cooling benefit across the entire precinct was relatively insignificant.

Figure C-35. Subdivision scenario changing all lot sizes in Southlakes to be 1,000 m².

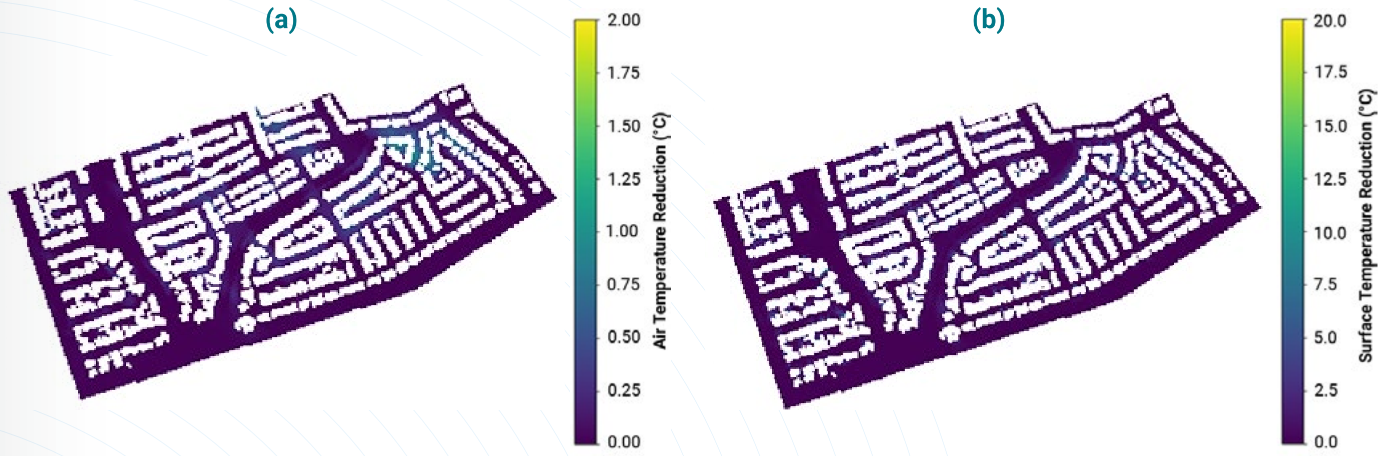

Figure C-36. (a) Air and (b) surface temperature reduction distributions at 2pm from changing all lot sizes to 1,000 m² in Southlakes.

Figure C-37. Hourly maximum (a) air temperature and (b) surface temperature reductions from changing all lot sizes to 1,000 m² in Southlakes.

- Subdivision Scenario: All 300 m² Lots -

The second subdivision scenario for Southlakes involved changing the existing lot sizes to be approximately 300 m² (Figure C-38). The existing lot sizes in Southlakes are predominantly 600 m² with some larger 2,000 m² lots, which means that there was a significant increase in housing density for this scenario. Additional roads were necessary in this scenario to accommodate the increased density, but the existing tree canopy coverage and proportion of dark roofs remained the same as the base case scenario. Townhouses were also added to this scenario near public spaces, which is in alignment with other higher-density residential development areas in Dubbo. The purpose of this scenario was to investigate whether increased density and hard surfaces would negatively affect Southlakes during extreme heat events, and if so, to what extent.

Figure C-39 shows the distribution of air and surface temperature increases at 2pm from changing all lot sizes to be 300 m² in Southlakes. This is likely due to the addition of streets and laneways to accommodate the increased density. The air temperature increases were generally higher in the areas where townhouses have been added in this scenario. Figure C-40 shows that the maximum air and surface temperature increases from increasing density in Southlakes were 1.1 °C and 19.4 °C respectively at 1pm. It also shows that there was a minor increase in air and surface temperature throughout the evening, which can have a significant impact on the health and wellbeing of Southlakes residents.

Figure C-38. Subdivision scenario changing all lot sizes in Southlakes to be 300 m².

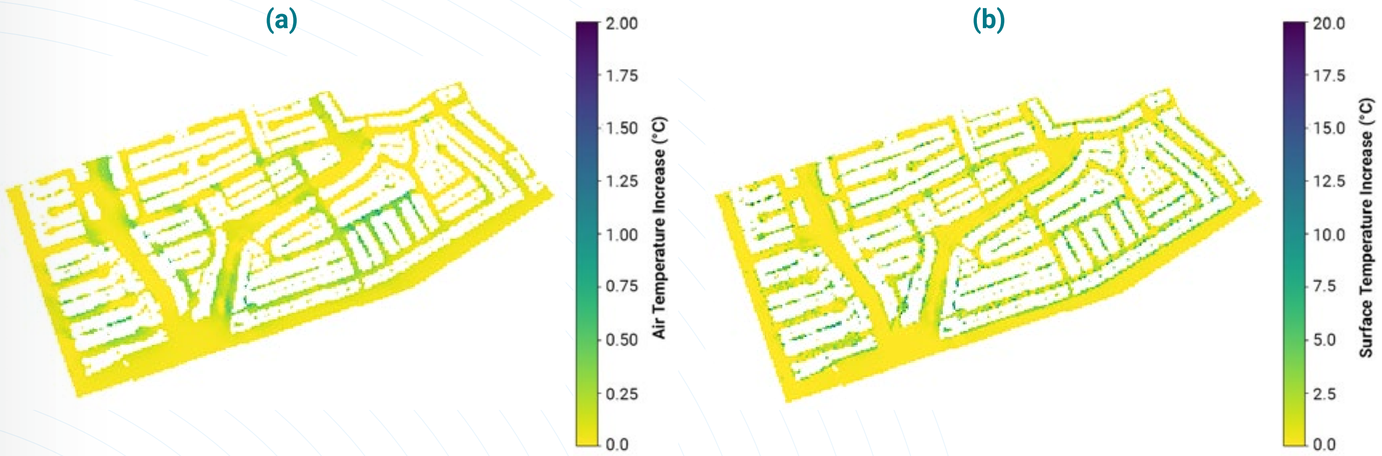

Figure C-39. (a) Air and (b) surface temperature increase distributions at 2pm from changing all lot sizes to 300 m² in Southlakes.

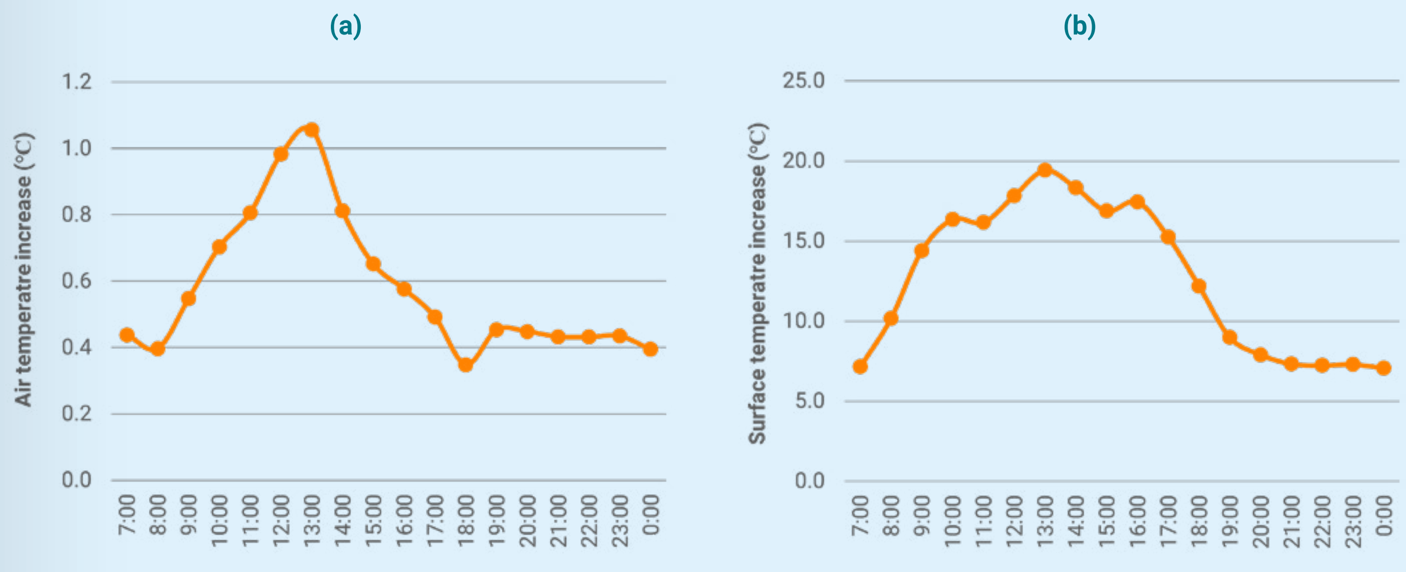

Figure C-40. Hourly maximum (a) air temperature and (b) surface temperature increases from changing all lot sizes to 300 m² in Southlakes.

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- Subdivision Scenario: All 300 m² Lots with Increased Green Open Space -

The third subdivision scenario for Southlakes involved the same increased density of 300 m² lots from the previous scenario combined with increased green open space. The quantity of additional green open space was guided by the desired ratio of parks to population defined by Dubbo Regional Council's Open Space Masterplan[60]. Approximately 3.2 ha of additional green open space was included in this scenario, which also incorporated increased tree canopy coverage. Figure C-41 shows the location of these additional green open spaces, which were distributed throughout the precinct in areas further away from the existing green open spaces of Southlakes.

Figure C-42 shows the air and surface temperature reduction distributions at 2pm for this scenario. These heatmaps show the localised cooling benefit produced by these additional green open spaces compared to the existing base case conditions of Southlakes. Figure C-43 shows that the maximum air and surface temperature reductions from this increased density scenario with additional green open space was 0.9 °C and 12.5 °C respectively during the middle of the day. The magnitude of precinct-wide air and surface temperature reductions for this scenario were comparable to the first subdivision scenario with decreased density (i.e. 1,000 m² lots).

Figure C-41. Subdivision scenario changing all lot sizes in Southlakes to be 300 m² with additional green open space (shown in green).

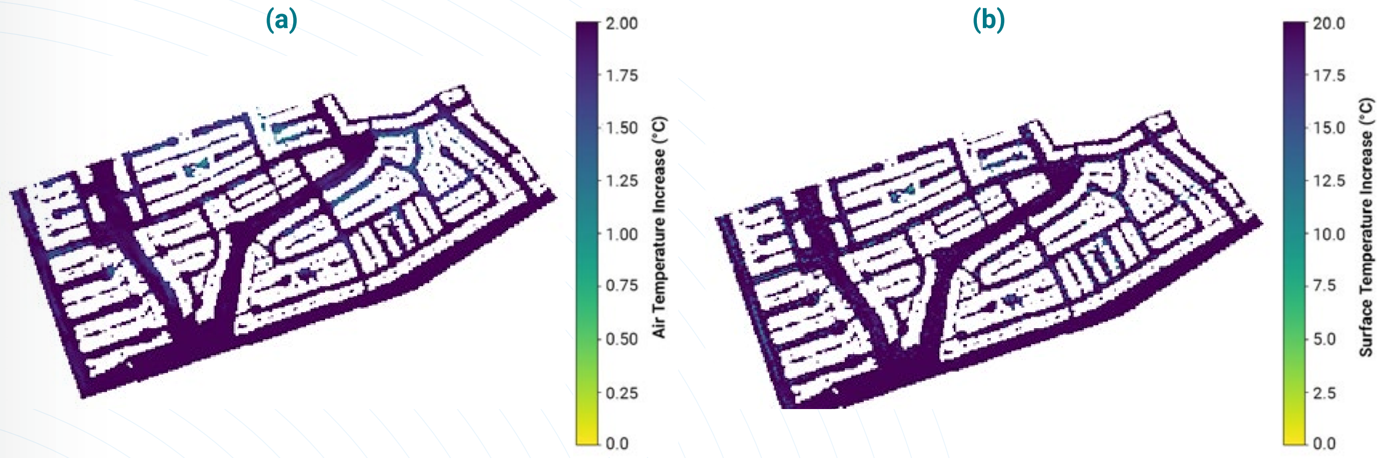


Figure C-42. (a) Air and (b) surface temperature reduction distributions at 2pm from changing all lot sizes to 300 m² in Southlakes with increased green open spaces.

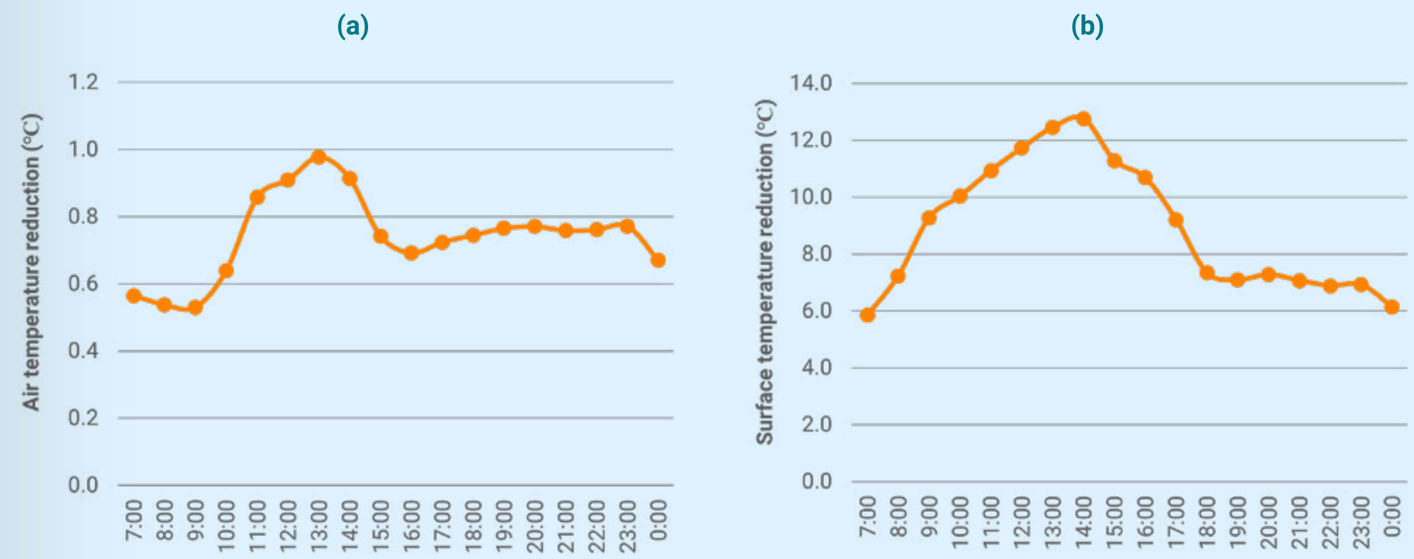


Figure C-43. Hourly maximum (a) air temperature and (b) surface temperature reductions from changing all lot sizes to 300 m² in Southlakes with increased green open spaces.

- Subdivision Scenario: All 300 m² Lots with a Combination of All Interventions Including Water Misting and Outdoor Shading -

This final subdivision scenario for Southlakes involved the 300 m² lots and additional green open spaces from the previous scenario and a combination of mitigation strategies. This combination included increasing public and private greenery, cool materials for all roofs, roads, pavements, and hard surfaces, and the addition of outdoor shading and water misting based on existing hot spots throughout Southlakes (Figure C-44). Therefore, this scenario represents the maximum possible cooling impact for Southlakes whilst substantially increasing its density.

Figure C-45 shows the air and surface temperature reduction distributions at 2pm from this combination of mitigation strategies with increased density in Southlakes. These heatmaps show the significant cooling benefits of this combined subdivision scenario, especially the localised impacts from the outdoor shading and water misting. Figure C-46 shows that the maximum air and surface temperature reductions possible from this scenario were 1.9 °C and 16.5 °C respectively during the middle of the day. There was also a relatively significant cooling impact throughout the evening. These results suggest that it is possible to simultaneously increase density and effectively reduce the impacts of urban overheating in Southlakes. In fact, comparing these results to the combination mitigation scenario without any subdivision changes, this scenario offered a slightly higher cooling benefit. This is likely due to the increased greenery and green open spaces of this scenario, and the higher overall proportion of cool reflective surfaces.

Figure C-44. Subdivision scenario changing all lot sizes in Southlakes to be 300 m² with a combination of mitigation strategies (coloured as per previous scenarios).

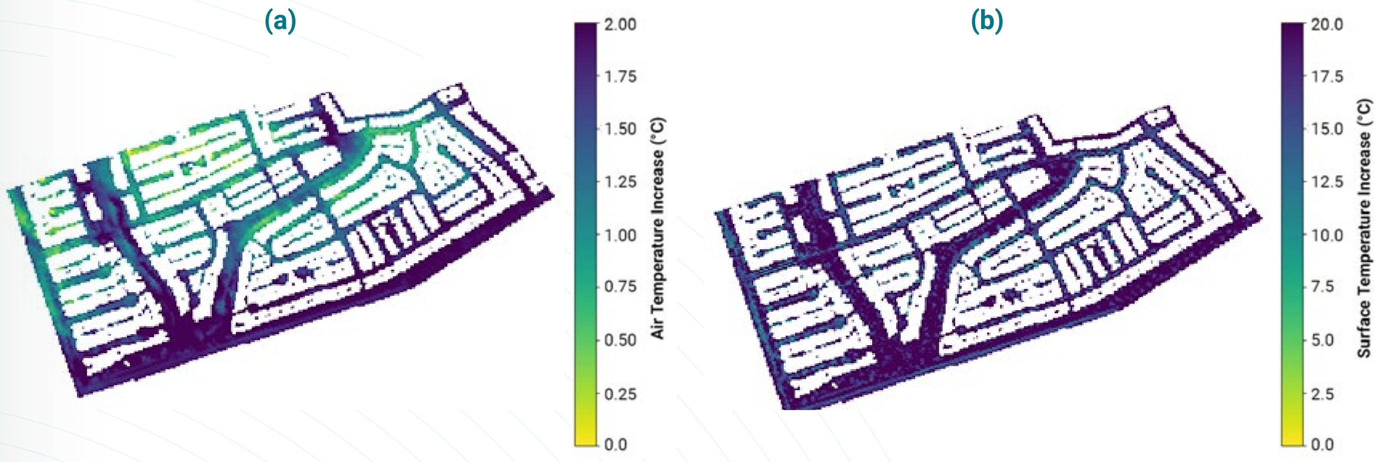


Figure C-45. (a) Air and (b) surface temperature reduction distributions at (a) 2pm from changing all lot sizes to 300 m² in Southlakes with a combination of mitigation strategies including water misting and outdoor shading.

Figure C-46. Hourly maximum (a) air temperature and (b) surface temperature reductions from changing all lot sizes to 300 m² in Southlakes with a combination of mitigation strategies including water misting and outdoor shading.

C.5.4 Cooling Potential of Mitigation Strategies in South Dubbo

In contrast to the new development of Southlakes, Dubbo Regional Council was also interested in understanding and reducing heat vulnerability in existing areas of Dubbo. The South Dubbo precinct was identified as an appropriate case study area to demonstrate this as it is a well-established area of Dubbo with a diversity of built environment characteristics. The western and eastern areas of South Dubbo comprise the low-density detached residential houses, which have a high proportion of dark roofs resulting in high surface temperatures (shown in yellow and red in Figure C-47). Most notably, South Dubbo has the highest proportion of green open space compared to the other precincts in the Phase 1 Pilot of the NaHVO resulting from the large sporting field in the centre of the precinct. This green open space shows well irrigated areas of grass can have significantly lower surface temperatures (shown in light blue in Figure C-47) than unirrigated areas, which in this case are comparable to the adjacent asphalt roads (show in red in Figure C-47). Other areas in South Dubbo include a gated community of townhouses with substantial green open space and tree canopy coverage to the north-west, and a school campus with large exposed dark roofs and hard surfaces located next to the sports field. The detailed built environment characteristics and heat vulnerability challenges for South Dubbo are provided in Table C-5.

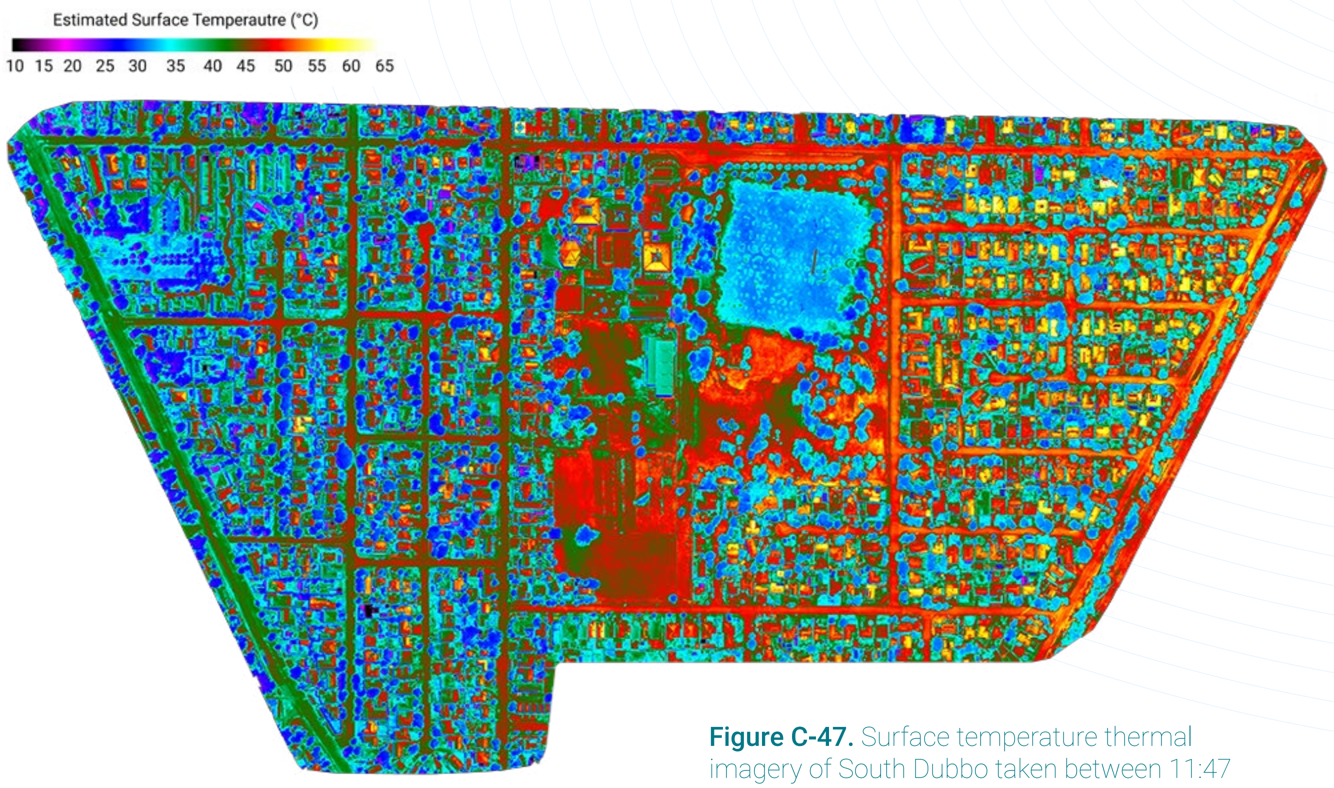
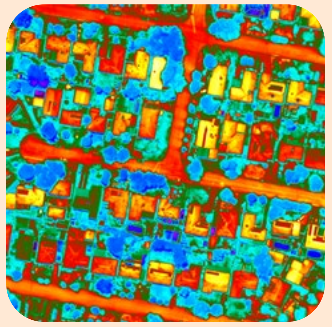
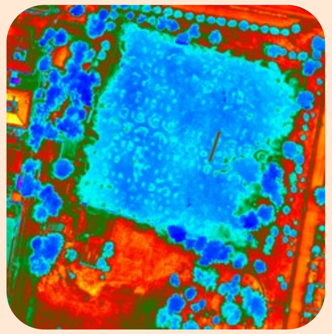
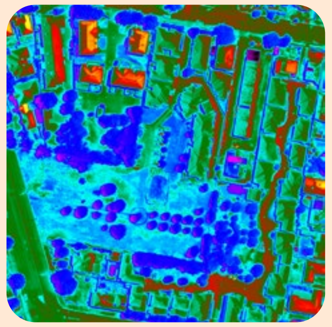
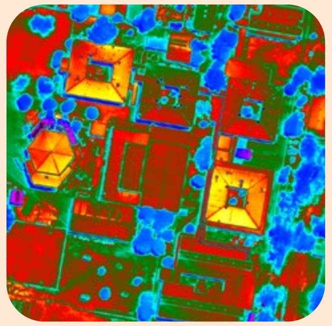


Figure C-47. Surface temperature thermal imagery of South Dubbo taken between 11:47 am and 2:53 pm on 10 November 2023.

View of South Dubbo via drone aerial photography (UNSW High Performance Architecture).

South Dubbo was included in the Phase 1 pilot of the NaHVO to investigate the maximum cooling potential across these diverse built environment characteristics of a well-established residential area. There are two heat mitigation scenarios for South Dubbo. First, the base case of its existing conditions, and second, a combination of mitigation strategies. The maximum cooling potential results of the combined mitigation scenario are presented in this section as reductions in air and surface temperature from the base case scenario for South Dubbo.

Table C-5. Built environment characteristics and heat vulnerability challenges in South Dubbo.

THERMAL IMAGERY	AERIAL IMAGERY	STREETSCAPE	BUILT ENVIRONMENT CHARACTERISTICS	HEAT VULNERABILITY CHALLENGES
			» Low-rise detached residential buildings with a compact layout. » Small to moderate areas of pervious and impervious private open space with some trees. » Narrow roads with low to moderate street tree canopy coverage. » High proportion of dark-coloured roofs.	» Exposed private open space due to limited private tree canopy. » Exposed hard surfaces with high surface temperatures along streets from limited tree canopy. » Narrow roads limit the opportunities for raingardens and outdoor shading. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Public green open space with moderate tree canopy coverage and large sporting fields.	» Areas of unirrigated and unshaded grass have higher surface temperatures.
			» Dense gated residential communities with substantial shared green open space and moderate tree canopy coverage. » Higher proportion of hard surfaces in other areas due to increased density. » Low proportion of dark-coloured roofs.	» Exposed hard surfaces with high surface temperatures surrounding the residential dwellings due to increased density. » Dark-coloured roofs can severely impact indoor thermal discomfort during high temperature days.
			» Education campus with large low-rise buildings. » Mixture of pervious and impervious surfaces for carparking, school facilities and playgrounds, with low to moderate tree canopy coverage. » Moderate proportion of dark-coloured roofs.	» Dark-coloured roofs can severely impact indoor thermal discomfort and student learning outcomes during high temperature days. » Areas of unirrigated and unshaded grass have higher surface temperatures. » Unshaded sporting and recreational areas can increase the likelihood of heat stress and heat stroke for students during high temperature days.

- Base Case -

Figure C-48 shows the modelled existing conditions of South Dubbo including 3D building objects and trees, road and footpath networks, and its large green open space. This was generated from a wide range of data sources from Dubbo Regional Council, open-source datasets, and satellite imagery (see Report D for more detail). This model of South Dubbo was used to simulate a base case scenario, which formed the basis to compare the combined mitigation scenario against. As mentioned in Section C.5.1, this base case model was validated with on-site measurements for air temperature, relative humidity, wind speed and direction, and solar radiation to ensure the simulated results were as close as possible to reality.

Figure C-49 presents the air temperature distribution of the simulated base case at 2pm for the South Dubbo case study precinct. This heatmap shows the extensive cooling benefit provided by the large green open space in the centre of the precinct. This green open space provides a cooling benefit for the adjacent school campus and was approximately 2 °C less than its surrounding compact low-rise residential development typology.

Figure C-48. Modelled base case of the existing conditions of South Dubbo.

Tree canopy surrounding South Dubbo Oval (UNSW High Performance Architecture).

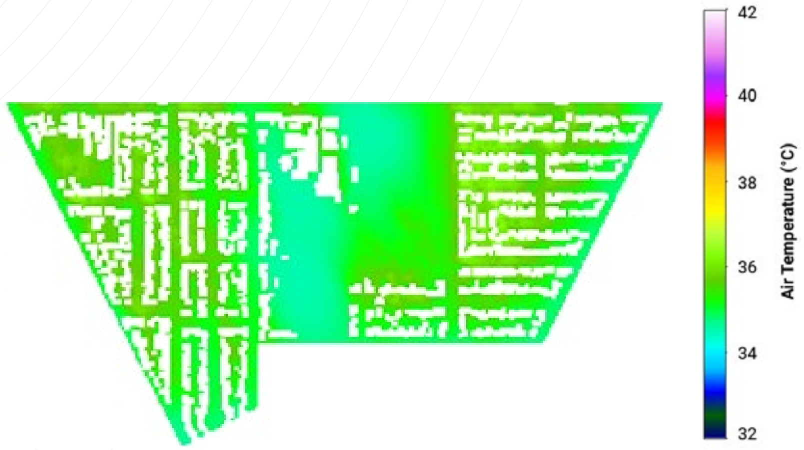


Figure C-49. Simulated air temperature distribution of the existing base case conditions of South Dubbo at 2pm.

- Cooling Potential of a Combination of All Interventions Including Water Misting and Outdoor Shading -

This scenario involved a combination of heat mitigation strategies for South Dubbo (Figure C-50). Firstly, this scenario added public and private greenery across South Dubbo. However, as the large green open spaces function as sporting fields, additional greenery was mainly placed alongside the main roads, which included some raingardens, and in private areas where possible. This scenario increased the total tree canopy coverage of South Dubbo by 2.8%. Secondly, it applied cool materials to all roofs, roads, pavements, and private hard surfaces. Finally, this scenario included the addition of outdoor shading and water misting located based on existing hot spots throughout South Dubbo. This cooling intervention scenario therefore represents the maximum possible cooling impact for South Dubbo without altering its existing built form, scale, and character.

Figure C-51 shows the air and surface temperature reduction distributions at 2pm from this combined mitigation scenario for South Dubbo. These heatmaps show substantial air and surface temperature reductions across the South Dubbo precinct. They also show the localised cooling benefits of the outdoor shading, water misting, and raingardens that were placed in existing hot spot areas throughout South Dubbo. The maximum cooling impact of this combination of mitigation strategies occurs during the middle of the day. Figure C-52 shows that maximum air temperature reductions above 1 °C were stable throughout the day and evening, and a maximum surface temperature reduction of 14.5 °C at 1pm.

Figure C-50. Combination of all cooling interventions in South Dubbo (coloured as per previous scenarios for Southlakes).

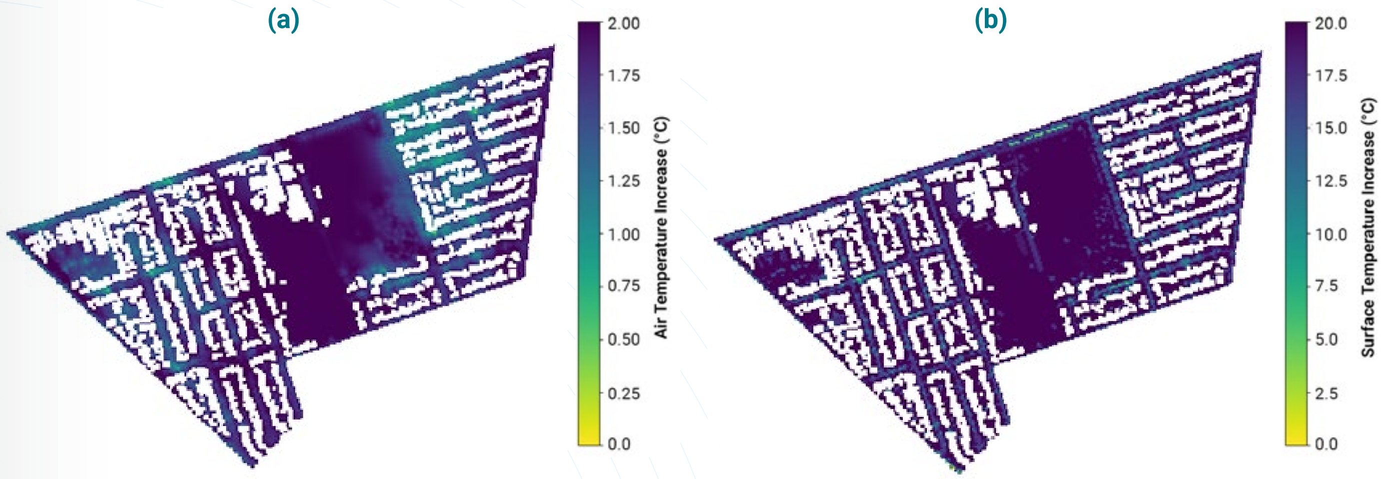


Figure C-51. (a) Air and (b) surface temperature reduction distributions at 2pm from a combination of all mitigation strategies including water misting and outdoor shading in South Dubbo.

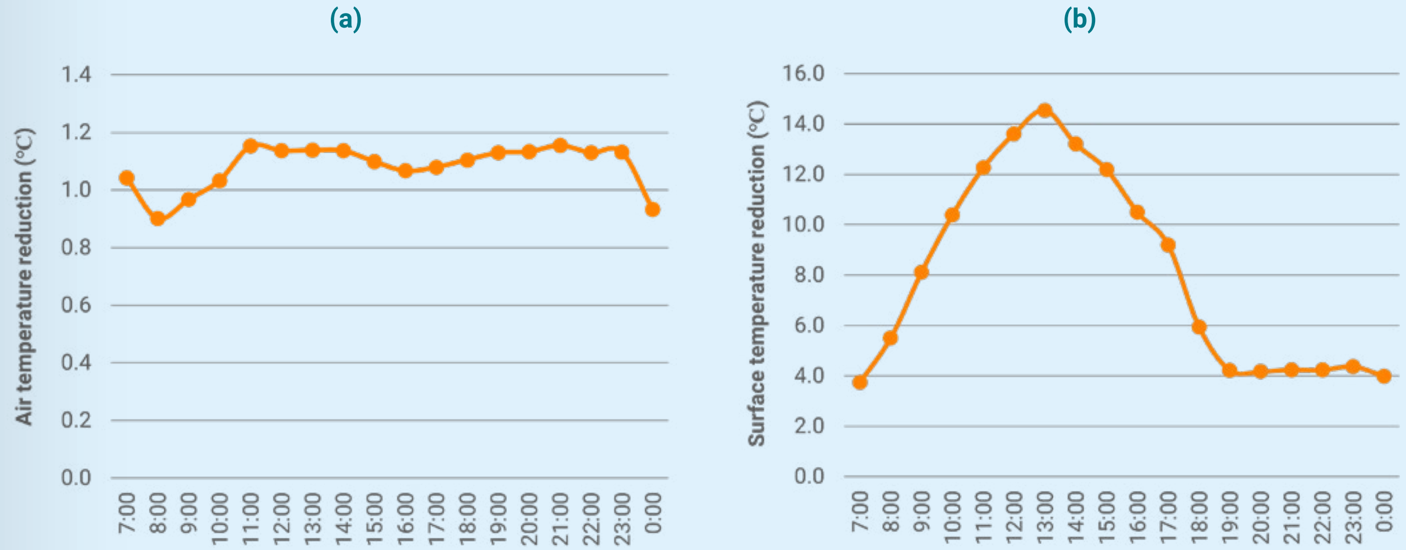


Figure C-52. Hourly maximum (a) air temperature and (b) surface temperature reductions from a combination of all mitigation strategies including water misting and outdoor shading in South Dubbo.

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Report D: Data Interoperability

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D.1 Introduction

Report D presents a feasibility study of data interoperability for the National Heat Vulnerability Observatory (NaHVO) Index and benchmark data. It offers an ontology-based framework for representing comprehensive heat vulnerability datasets with their interrelations. It provides data collection protocols, including data categories, sources and processes, which enables a consistent approach to establishing NaHVO benchmark datasets for more cities in Australia. Additionally, it provides a preliminary NaHVO data structure that supports various views for connections to other government platforms, along with examples of connections to the NSW Digital Twin platform.

D.2 Data Interoperability through Ontology

D.2.1 Ontology

Ontology provides a systematic approach to interpreting domain knowledge, concepts, processes, their properties, and interrelations[61]. An ontology-based data representation method creates data entities, properties and interrelations for domain data, enabling a computational data representation that supports database structure development and heat vulnerability analytics.

This project focuses on data interoperability rather than software interoperability. An ontology-based approach is employed to represent the NaHVO benchmark datasets as defined in Section A.3.1. This method helps in understanding and formatting the concepts, classifications and interrelations of benchmark datasets in the NaHVO Index, supporting data interoperability with other government platforms.

D.2.2 An Ontology-Based Framework for Representing Heat Vulnerability Benchmark Datasets

An ontology-based conceptual framework for representing heat vulnerability benchmark datasets is illustrated in Figure D-1. It describes ontological features of key influential factors, such as the built environment heat vulnerability profile and the community heat vulnerability profile, along with key performance indicators, including local urban heat, heat-related morbidity and mortality, and electricity use impacts. Additionally, it includes cooling intervention options that could improve the built environment heat vulnerability profile, thereby reducing the heat vulnerability level. Data concepts and various interrelations are presented hierarchically in this framework.

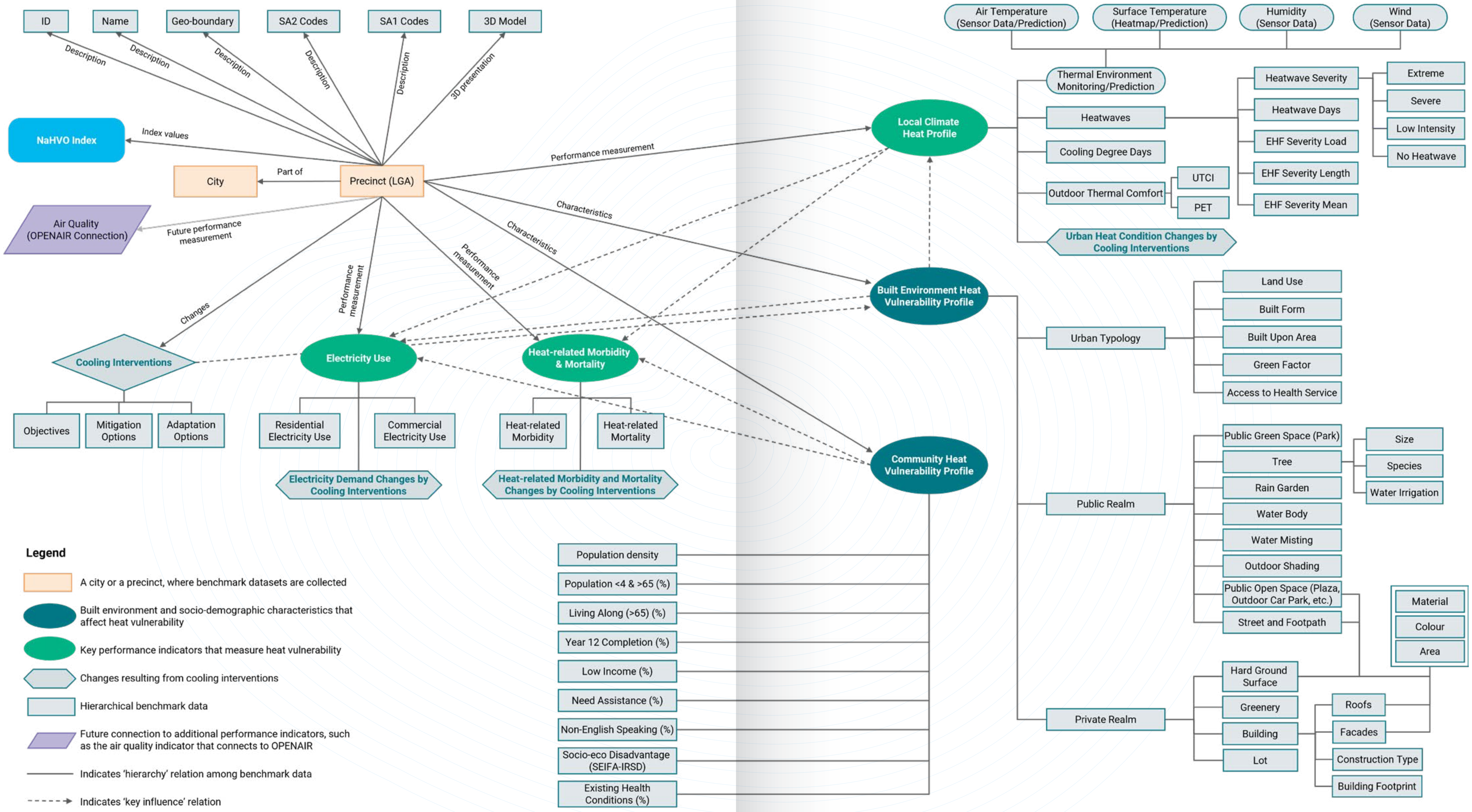

Figure D-1. An ontology-based conceptual framework for representing heat vulnerability benchmark datasets.

D.3 Data Collection Protocols

D.3.1 Data Categories and Sources

The NaHVO benchmark datasets described in the ontology-based conceptual framework (Figure D-1) can be grouped into eight categories and collected from various sources. Table D-1 provides a description of each data category and the sources from which they can be collected. It is worth noting that alternative sources may be available for specific data, and format changes for data may occur in future. Additionally, there are data privacy, licensing, and legal concerns, particularly regarding heat-related mortality and morbidity data, and building energy consumption data.

D.3.2 Data Collection and Preprocessing

There are preprocessing requirements for some of the NAHVO benchmark datasets. Detailed information on individual attributes, collection processes and preprocessing requirements are provided as follows.

ABS SA1 and SA2 Boundaries

ABS Statistical Area Level 1 (SA1) and Statistical Area Level 2 (SA2) are identified for data collection and analysis. These datasets are publicly available through the ABS website in various formats, requiring little to no additional processing.

Cities

3D models of a city or precinct include key city objects such as streets, trees, parks, water bodies, plazas, etc., along with their attributes such as materials, size and location. These datasets are used for analysing built environment characteristics for the NaHVO Index, modelling and simulation of mitigation and adaptation strategies, 3D visualisation of the study area, and the what-if scenario analysis to support urban planning decision-making.

Building footprints and heights are collected to generate 3D bounding boxes of buildings at a city or precinct level. 3D bounding boxes of buildings in some cities are available from the spatial information providers such as Geoscape Australia (formerly PSMA) under licenses. If they are not available, data preprocessing is required, which can be conducted through various modelling software tools such as SketchUp, ArcGIS, and FME.

Table D-1. Data categories and sources.

DATA CATEGORY	DESCRIPTION	SOURCE
ABS SA1 and SA2 boundaries	Australian Bureau of Statistics (ABS) statistical area level 1 (SA1) and statistical area level 2 (SA2)	» ABS
Cities	3D models of the study area, including key city objects such as roads, water bodies, trees, parks, etc. and their attributes.	» World urban database (WUDAPT), Landsat 8 » Spatial information providers such as Geoscape Australia (former PSMA) » Local governments » Master plans from developers » OpenStreetMap » Microsoft Building Footprints (Bing Maps) » Nearmap » NSW Digital Twin » NSW Department of Climate Change, Energy, the Environment and Water » NSW Department of Planning, Housing and Infrastructure
Buildings	3D models of buildings (geo-referenced) in the study area and their attributes. Multiple Level of Details (LOD) may be required for different purposes.	
Socio-demographics	Population information for SA1 and SA2 in the study area.	» ABS » Local governments
Electricity consumption	Aggregated electricity usage data of buildings for SA1 and SA2 in the study area.	» Utility providers » NSW Department of Climate Change, Energy, the Environment and Water
Heat-related morbidity and mortality	Emergency department presentations for selected heat-related medical codes, and the Cause of Death Unit Record File for selected heat-related medical codes for SA1 or SA2 in the study area.	» NSW Ministry of Health » Data custodians (which provide datasets containing information of deaths registered in Australia)
Urban heat measurement	Monitoring air temperatures, surface temperatures, humidities and winds in the study area.	» Sensors » Drone » BoM » Heatmap providers
	Heatwave information in the study area	» BOM
	Predicted information including changes in air and surface temperatures due to mitigations, cooling degree days (CDD), and outdoor thermal comfort (UTCI and PET) in the study area.	» Modelling and simulation » Calculation algorithms
Urban heat mitigation and adaptation	Urban heat mitigation and adaptation strategies in the study area proposed by governments, developers or designers.	» Governments, developers or designers » Local Environmental Plan » Local Planning Controls

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Buildings

Detailed building models include construction types and materials along with other attributes, in addition to 3D bounding boxes of buildings. These datasets are used for analysing building characteristics including roofs and facades for the NaHVO Index, modelling and simulation of mitigation and adaptation strategies including an energy consumption analysis, and 3D visualisation of buildings with a certain level of detail. Data preprocessing is required for building models to ensure that the necessary information is available for modelling and simulation.

Socio-demographics

Population information for SA1 and SA2 in the study area is collected from the ABS. Local governments may also provide specific population information on demand. Table D-2 lists key population information that contributes to the Community Heat Vulnerability Profile in the NaHVO Index. Tabular data from the ABS Census is extracted and processed into a single tabular format for the NaHVO Index.

Table D-2. Population information.

Population Information in the Study Area	Unit	Source
Total Population	People	ABS
Population Density	People / km2	
Percentage of Population <4 & >65 Years Old	%	
Percentage of Population >65 Years Old and Living Alone	%	
Percentage of Population Completed Year 12 (or equivalent)	%	
Percentage of Population Speaking a Language Other Than English at Home	%	
Percentage of Population Needing Assistance with Core Activities	%	
Percentage of Population with One or More Long-Term Health Conditions (Arthritis, asthma, cancer (including remission), dementia (including Alzheimer's), diabetes (excluding gestational diabetes), heart disease (including heart attack or angina), kidney disease, lung condition (including COPD or emphysema), mental health condition (including depression or anxiety), stroke, any other long-term health condition(s))	%	
Socio-Economic Disadvantage (SEIFA-IRSD Socio-Economic Indexes)	Decile	
Percentage of Population in Low Income Households (<$800/week)	%	

Electricity Consumption

Aggregated electricity usage data of buildings for SA1 and SA2 in the study area are collected from the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) for this project. Alternatively, these datasets can be obtained from utility providers with the support of local governments. The data are measured monthly and divided into business and residential electricity use respectively. In the future, where possible, daily electricity usage data could be collected where possible to enable the analysis of energy use behaviour during heatwaves. Table D-3 lists the monthly electricity consumption information, where only residential connections are included in the Phase 1. Little data preprocessing is required.

Table D-3. Electricity information.

Electricity Consumption information in the Study Area	Unit	Source
Total monthly electricity use for all residential connections	kWh/NMI	NSW DCCEEW or utility providers
Total monthly electricity use for all business connections		
Total monthly electricity use for all residential and business connections		
Average monthly electricity use for residential properties		
Average monthly electricity use for business properties		
Average monthly electricity use for residential and business properties		

Heat-related Morbidity and Mortality

Emergency department presentations and the Cause of Death Unit Record File for selected heat-related medical codes are collected from the NSW Ministry of Health and relevant data custodians. Obtaining such datasets requires an ethics application. Where possible, detailed heat-related health data, such as daily emergency department presentations, will be utilised for health impact analysis. Data preprocessing is necessary to identify heat-related medical codes, with the support of public health experts. Table D-4 present medical ICD-10 codes covering health outcomes that could result from heat, which have been used in Phase 1.

Table D-4. Medical ICD-10 codes covering health outcomes that could result from heat, which have been used in Phase 1 (Source: Dr Matthew Anthony Borg and Professor Peng Bi, School of Public Health, University of Adelaide)

Health outcome category	ICD-10	Rationale
Heat-related illness	T67, E86, X30	Heat-related illness codes specifically capture the direct impacts of heat exposure on health outcomes, including heatstroke, dehydration, and other heat-related conditions. These codes are essential to directly assess the health consequences of heat exposure.
Cardiovascular	I00-I99	Direct mechanisms: Heat can increase heart rate, blood pressure, and blood viscosity, promoting the development of cardiovascular events such as heart attacks and strokes. Indirect mechanisms: Heat-related dehydration and electrolyte imbalances can strain the cardiovascular system and exacerbate pre-existing conditions.
Mental Health	F00-F99	Direct mechanisms: Heat-related physiological stress responses can contribute to psychological distress, anxiety, and mood disturbances. Indirect mechanisms: Heat-related sleep disturbances, social disruptions, and environmental changes can impact mental health.
Diabetes	E10-E14	Direct mechanisms: Heat can affect glucose metabolism and insulin action, potentially leading to hyperglycemia and metabolic complications in individuals with diabetes. Indirect mechanisms: Heat-related dehydration and electrolyte imbalances can impact diabetes management and glycemic control.
Renal	N00-N39	Direct mechanisms: Heat-related dehydration and reduced renal blood flow can strain the kidneys and contribute to renal dysfunction. Indirect mechanisms: Heat-related electrolyte imbalances and changes in fluid and sodium balance can impact renal function and exacerbate renal conditions.

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Urban Heat Measurement

Urban heat measurement data are obtained through various methods, including real-time monitoring of air temperatures, humidities, winds and solar radiation through sensors, collection of surface temperatures via drones, heatwave data collection from the BOM, and predicted data generated through modelling and simulation, or algorithm-based calculations. Data pre- and post-processing is necessary for predicted data such as Cooling Degree Days (CDD) and outdoor thermal comfort metrics (UTCI and PET). The heatwave datasets for Phase 1 were provided on a daily basis and then aggregated to monthly data. The heatwave datasets (Table D-5) require data preprocessing to extract the relevant geographical grids (0.05 degrees or approximately 5 km) and convert the multidimensional NetCDF files from the BOM to a tabular format. This can be achieved using Python scripts.

Table D-5. Heatwave information.

Heatwave Information in the Study Area	Unit	Source
Excess heat factor severity (EHFsev) - Extreme: EHFsev ≥ 3, Severe: 1 ≤ EHFsev < 3, and Low intensity: 0 < EHFsev < 1	Category/ Number	BOM
Monthly heatwave days	Days	
Monthly average EHFsev	Category/ Number	

Urban Heat Mitigation and Adaptation

Urban heat mitigation and adaptation options for the study area are identified through a co-design process with local governments to address local urban heat issues. These options are then modelled and simulated to predict their cooling potential.

Heat-related morbidity and mortality data, and electricity consumption data described in this report, have been obtained in aggregate form. This aggregation ensures that no personal data can be extracted, thereby maintaining privacy. Future iterations of the NaHVO benchmark datasets may require the use of de-anonymised data. In such cases, procedures and certifications to ensure appropriate storage and handling of the data will be established. The design of the NaHVO data repository in this report (refer to Section D.4.1) accounts for the possibility that data with privacy concerns could be hosted externally and accessed only through an application program interface (API). This would provide anonymised results of queries run on the raw data. Such an approach provides a smart solution for addressing potential privacy implications in the future.

D.3.3 Database Repository Structure

A preliminary structure of the NaHVO data repository is provided in Figure D-2 (next page), and detailed data specifications are provided in Appendix 4. The data repository structure has been developed to support the interrelations defined in the ontology-based conceptual framework (Figure D-1) for benchmark datasets, the retrieval of these benchmark datasets, and the prediction results from modelling and simulation of cooling interventions. For example, sensor data or heatmaps collected by a drone can be linked to the existing state of the built environment.

Additionally, the data repository structure has been designed to support the importing or exporting of data through APIs compatible with specific government platforms. For instance, sensor data monitoring urban heat in the NaHVO data repository are structured to support import and export in formats consistent with the OPENAIR APIs to facilitate future connections to the OPENAIR platform (Figure D-3).

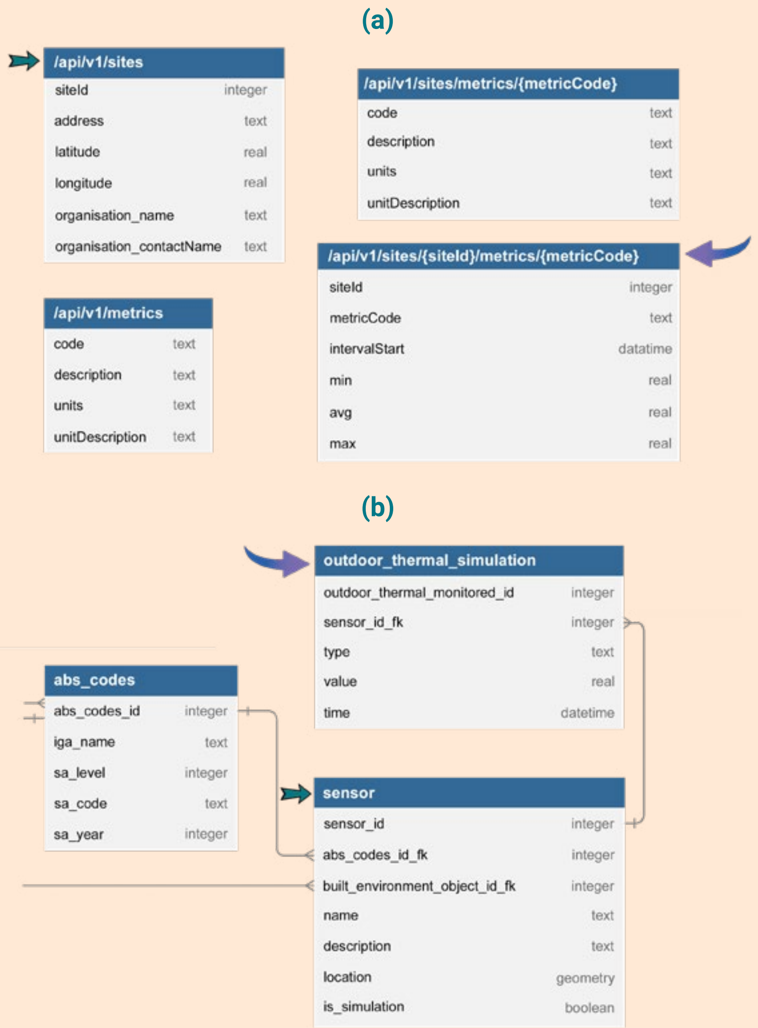

Figure D-3. An example showing how sensor data monitoring urban heat in the NaHVO data repository are structured to support import and export in formats consistent with the OPENAIR APIs. (a) data structure for accessing sensor data in OPENAIR, and (b) data structure storing sensor data in NaHVO.

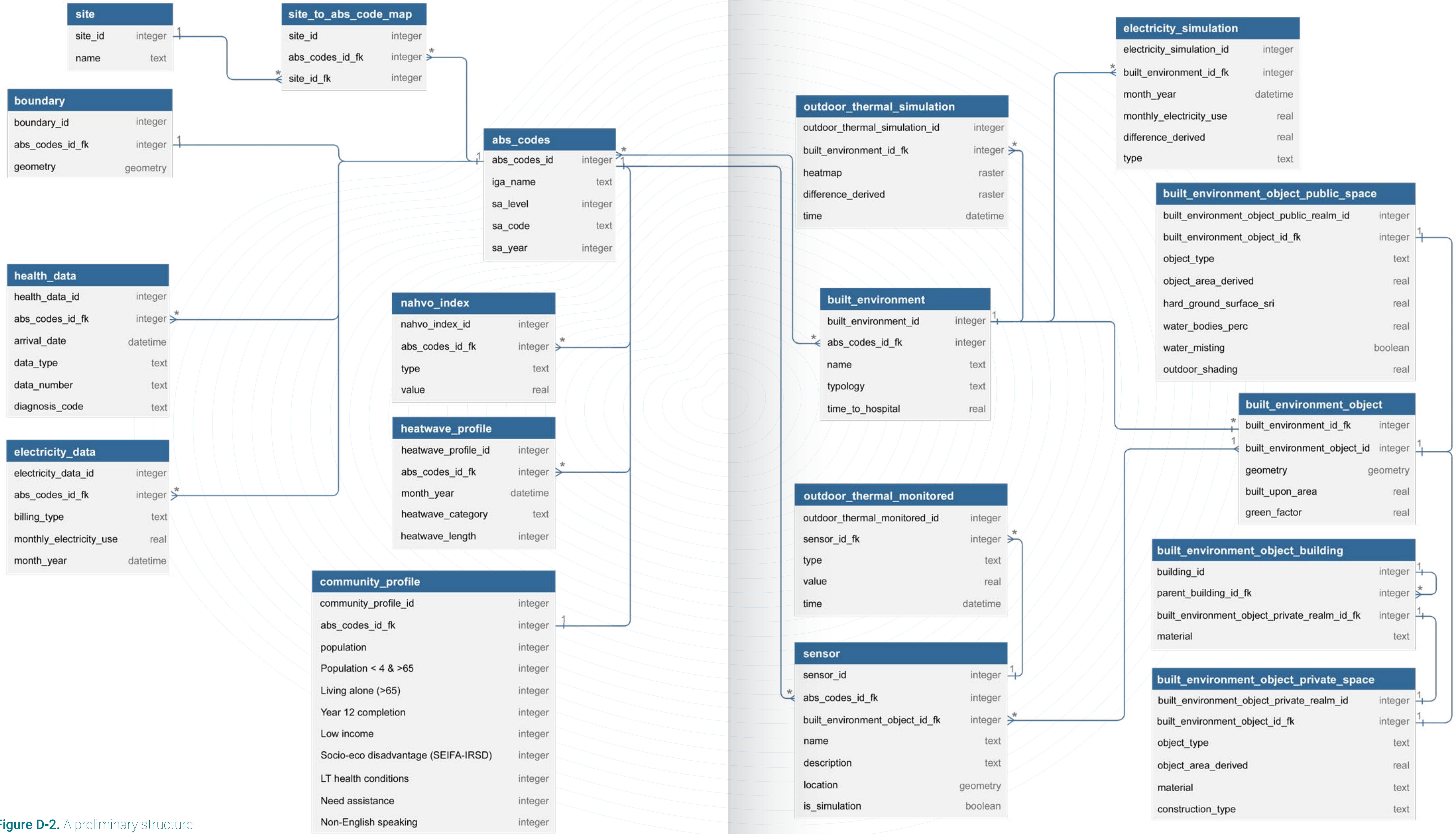

Figure D-2. A preliminary structure of the NaHVO data repository.

D.4 Feasibility Study of Connections to Government Platforms and NSW Digital Twin

D.4.1 Design for Pilot Connections

The NaHVO benchmark datasets, both collected and predicted, are stored in a central repository named the NaHVO Repository, as shown in Figure D-4. This data repository provides various views to support connections to external applications' APIs. It allows not only storing raw datasets, such as sensor data through ingestion services like scripts, servers, or manual processing, but also incorporating externally stored

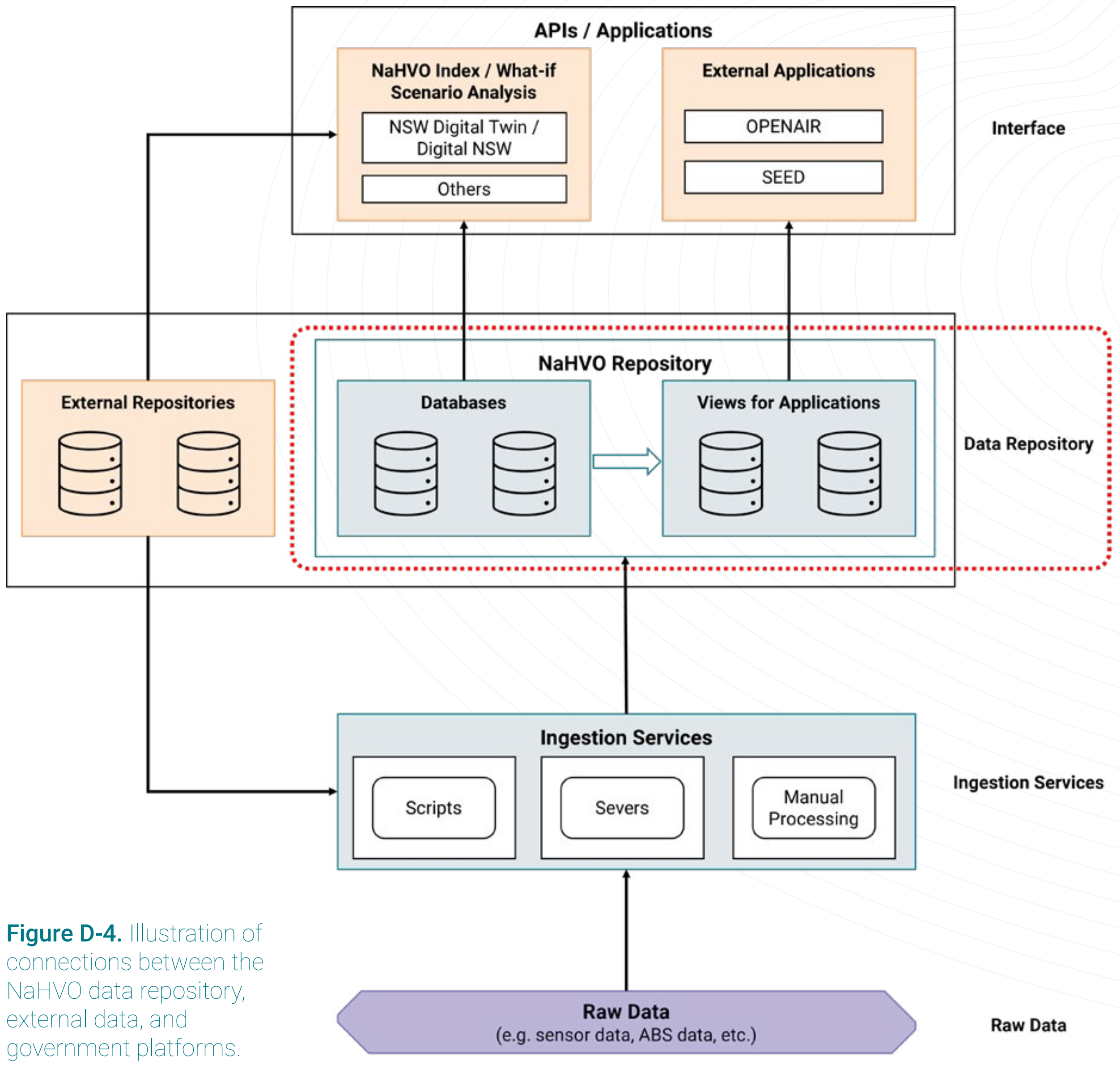

Figure D-4. Illustration of connections between the NaHVO data repository, external data, and government platforms.

data containing sensitive information, such as health data. Queries to external databases can be formed as part of a view, meaning the aggregate, anonymised data along with the other data from the NaHVO Repository can contribute to the data query response.

User functions for the NaHVO Repository involve 3D visualisation of a city or a precinct, its NaHVO Index values, benchmark data and performance indicators, as well as what-if scenario analyses of cooling interventions. NaHVO Index values help in understanding existing vulnerability levels, while the what-if cooling potential analyses support decision-making for heat vulnerability reduction. These user functions can be established through a standalone platform or through connections with various government platforms, such as the NSW Digital Twin, OPENAIR and SEED platforms (Figure D-4).

D.4.2 Pilot Connections to NSW Digital Twin / Digital NSW

A feasibility study has been conducted for connections to the NSW Digital Twin, or Digital NSW, as developed by the NSW Government. The existing user function regarding 3D visualisation of a city or a precinct, along with additional user functions by connecting to the NaHVO Repository, are illustrated in Figure D-5. This figure shows the overall structure and user scenarios, including an evolving data repository with a specific view to support the connection with the NSW Digital Twin / Digital NSW, dynamic NaHVO Index values with performance indicators and contributing factors, and cooling intervention scenario analyses.

The feasibility study has focused on the database structure, data formats, and the manual importing or exporting of data for 3D visualisation of what-if scenario analyses. This includes cooling intervention options and their impacts on outdoor thermal environments, such as air or surface temperature reduction distributions.

An account was created by the NSW Digital Twin team for conducting this feasibility study. The 3D models of cooling intervention options for case study precincts in Maitland City and Dubbo Region were generated and geolocated by the UNSW team using SketchUp. They were then converted into ESRI Scene Layer Packages (SLPK) using FME Workbench for 3D visualisation on the NSW Digital Twin. The outdoor thermal environment impacts of cooling intervention options were visualised through heatmaps of air or surface temperature reduction distributions. This process involved handling a large number of output files

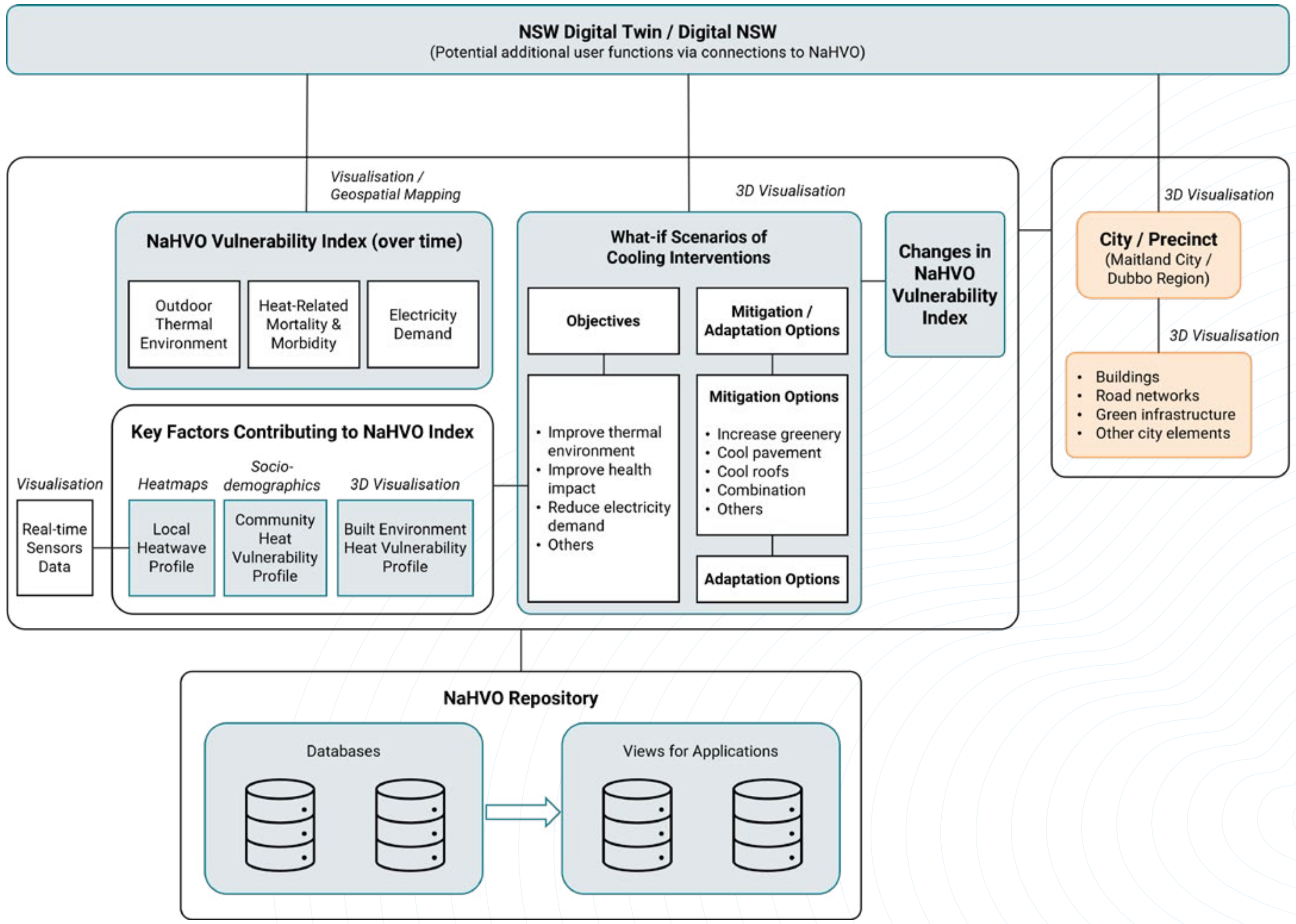

Figure D-5. Illustration of additional user functions by connecting the NSW Digital Twin / Digital NSW and the NaHVO Repository.

(such as EDX and EDT files) from the computational fluid dynamic software Envi-met. Data processing was required to produce these heatmaps (PNG files), which were then geolocated and converted into SLPK files for 3D visualisation on the NSW Digital Twin. Additional, time series of sensors data, along with locations of sensors, were available for visualisation on the NSW Digital Twin. Figure D-6 (a) and (b) show the 3D visualisation of outdoor thermal environments for the Aberglasslyn and Southlakes case study precincts respectively on the NSW Digital Twin. Figure D-6 (c) shows the 3D visualisation of air temperature reduction distributions resulting from a combination of cooling intervention options on the NSW Digital Twin.

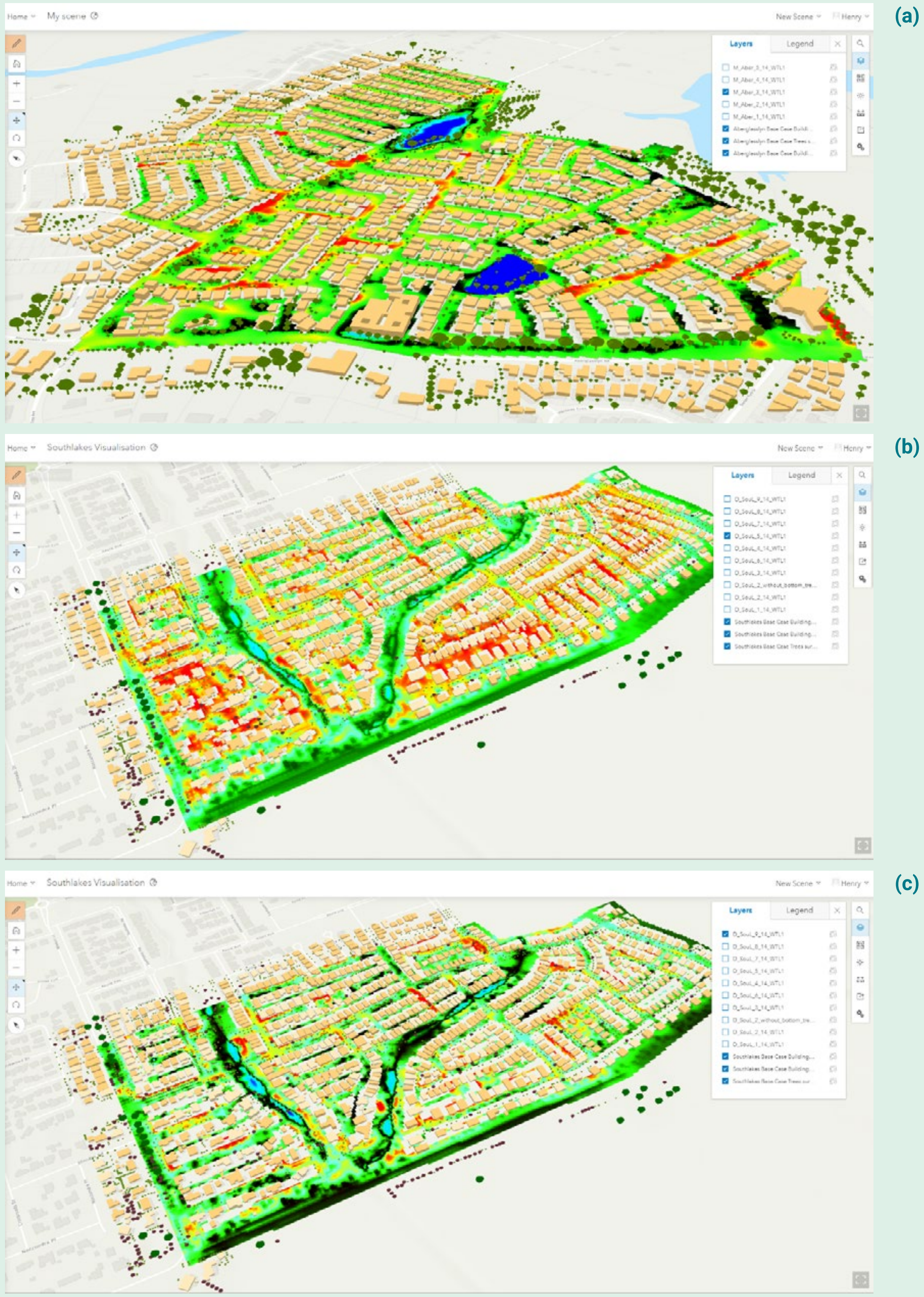

Figure D-6. 3D visualisation of outdoor thermal environments for the (a) Aberglasslyn and (b) Southlakes case study precincts on the NSW Digital Twin; and (c) the 3D visualisation of air temperature reduction distributions resulting from a combination of cooling intervention options on the NSW Digital Twin.

Figure D-7. A mock-up user interface for future development consideration for connections to government platforms.

In the future, automated processes and methods for connections with government platforms can be developed. This could involve facilitating API access for the automated importation of data from NaHVO Repository, including real-time sensor data. Eliminating manual data export for integration with government platforms will empower the impact of the NaHVO Repository. A mock-up user interface for future development consideration for connections to government platforms is shown in Figure D-7. Future scenarios include real-time monitoring heat vulnerability, 3D visualisation of what-if scenarios of mitigation and adaptation strategies and their impacts to support decision-making, and potential heat vulnerability reduction over time.

Key Recommendations

This section of the report provides a set of recommendations regarding heat mitigation and adaptation strategies for Maitland City Council and Dubbo Regional Council. These recommendations are established from the cooling intervention analysis results for the Maitland and Dubbo case study precincts, which were presented in Reports B and C. They are also informed by the UNSW High Performance Architecture (HPA) Research Cluster's past work on heat mitigation and adaptation, and the Urban Heat Island Mitigation Performance Index developed by UNSW and the CRC for Low Carbon Living. Therefore, some of these recommendations consider broader adaptation strategies as well as mitigation strategies for additional urban contexts across Maitland and Dubbo other than low-density residential areas. This section also includes some of the key considerations for various heat mitigation and adaptation strategies. It is acknowledged that these recommendations must be considered holistically with other key sustainability objectives such as reducing carbon emissions or increasing biodiversity.

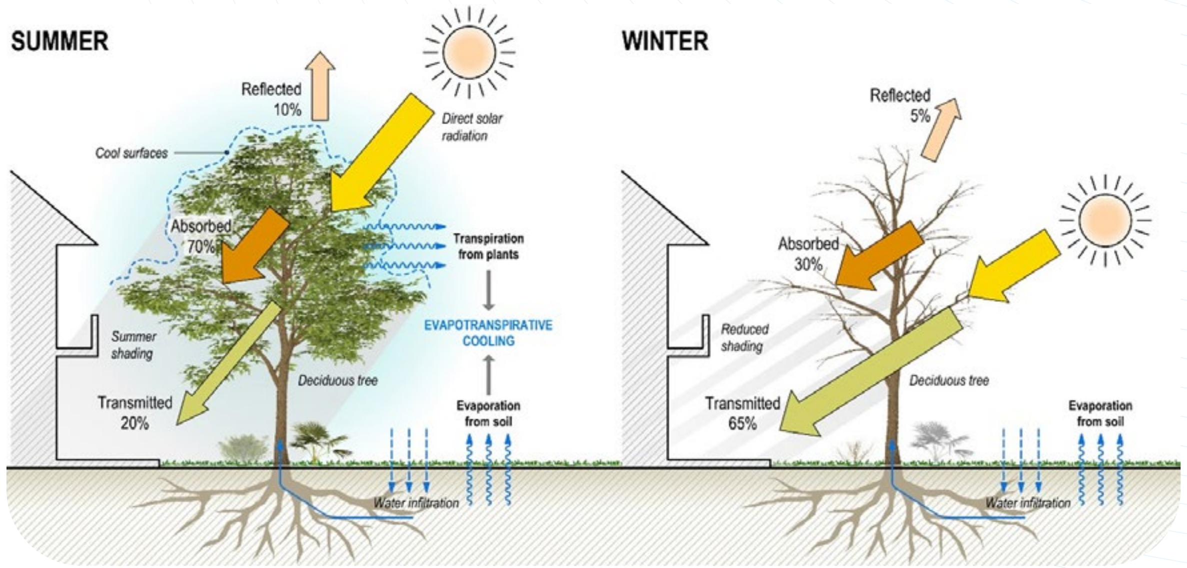

Figure R-1. Schematic diagram of the cooling effects of a tree in summer and winter[63].

Increase Tree Canopy Coverage

The cooling potential of increasing the number of trees in the public and private realms for all case study precincts in Maitland and Dubbo was shown to be an effective way to reduce air and surface temperatures during extreme heat events. Trees provide cooling through evapotranspiration and shading of hard surfaces, which can lower both air and surface temperatures (Figure R-1). In addition to cooling benefits, trees and urban greenery can provide effective stormwater management, improved air quality, increased biodiversity, and enhanced urban aesthetics[28]. Some of the key considerations for increasing the quantity and quality of trees are provided below.

- The design, pattern and palette of tree plantings should respond to the local area's specific characteristics (i.e. street orientation, level of pedestrian activity, sense of place, character, and type of surrounding activities/uses) and street sections (i.e. widths and heights of frontages).
- Plant and tree selections should be diverse and include Australian native and exotic species that suit existing soil conditions and are resistant to water and heat stresses[62]. Tools such as the 'Which Plant Where' can be used to identify appropriate tree species for future climate conditions.
- Constant and adequate soil and moisture conditions should be always provided depending on the type of species planted by (1) undertaking continuous trenching and soil improvements, (2) providing passive irrigation using harvested rainwater and stormwater runoffs, (3) planting trees in low-lying or drainage zones of the street, (4) installing permeable pavements in the vicinity of trees, and (5) constructing rainwater/stormwater infiltration pits near or next tree plantings[63, 64].
- Consistent and regularly spaced lines of trees with well irrigated grasses along the length of the street are recommended to provide constant solar protection and evapotranspiration during the day and facilitate wind circulation to ease heat dissipation at night[63]. Results from Dubbo show that care should be taken to understand how the interaction of prevailing wind conditions, street orientation, and tree density may impact the cooling potential of trees.
- Factors such as underground or overhead services, bridges and building awnings must be considered when determining planting configurations. Consider bundling and moving power cables underground to improve canopy coverage[62-64].
- Mixed understory verge planting (pervious surfaces, grasses and shrubs) or permeable surfaces should be always provided under or alongside trees. Low cover planting can include bioswales and raingardens in strategic locations. Flexibility for community driven initiatives like communal and edible gardens on public land should also be encouraged[62, 64].
- Where trees are in footpaths, deciduous trees should be favoured in south- and east-facing footpaths, evergreen trees in north- and west-facing footpaths, and trees in medians can be mostly evergreens[62-64].
- Although dense tree canopies can provide significant temperature reductions during the day, depending on context and plant species, very dense tree canopies may trap a significant number of pollutants[63].
- With increasing housing density, existing trees tend to be removed in favour of low-maintenance backyards or larger outdoor living areas. Consider incentivising developers and residents to keep existing trees and/or plant new trees on private land. For example, North Sydney Council is currently trialling the 'Trees for Newborns' program.

Improve the Amenity of Green Open Spaces

The cooling potential analysis results of the Maitland and Dubbo case study precincts has shown that green open spaces can provide localised air temperature reductions of 2 to 3 °C during extreme heat events. When combined with outdoor shading structures, small water bodies, water misting systems, and additional greenery, the localised cooling potential of these green open spaces can increase significantly. Conversely, without ongoing maintenance and irrigation, the effectiveness of these spaces can decrease. For example, the surface temperature of unirrigated grassed areas in South Dubbo Oval was found to be comparable to the adjacent dark asphalt road, which is approximately 20 °C warmer than the surrounding irrigated grass (Figure R-2). Some of the key considerations for increasing the amenity of green open spaces are provided below.

- Green open spaces should consider a higher proportion of vegetated spaces including lawn, shrubs, trees, water features, and permeable pavements than impervious surfaces. For any impervious surfaces, cool pavements (see below) should be prioritised over conventional pavements[62, 63].
- Passive irrigation systems and water sensitive urban design technologies should be implemented in green open spaces to ensure an effective evapotranspirative cooling, reduce stormwater runoffs, and facilitate water infiltration[63].
- A diverse palette of plants species and planting arrangements should be considered in the design of green open spaces, avoiding mass planting with single species. Plant selections should include Australian native and exotic species that are heat-resilient and drought tolerant[62]. Tools such as the 'Which Plant Where' can be used to identify appropriate tree species for future climate conditions.
- Consider the use of xeriscaping to reduce or eliminate the need for irrigation in green open spaces[65].
- Green open spaces should enable community driven initiatives like communal and edible gardens where possible[62].
- For existing hard surfaced areas such as car parks, surfaces can be partially or totally replaced by low plantings and permeable materials with extensive canopy crowns regularly distributed to increase shading[63].
- Any inclusion of outdoor shading devices should consider light-coloured, high albedo, and radiative cooling materials (see below) while ensuring that the negative effects of glare are minimised for those within the public realm. Shading devices may also consider integrating rainwater harvesting and evaporative cooling systems like misting sprays, provided it is not in a humid climate[23, 28, 66].

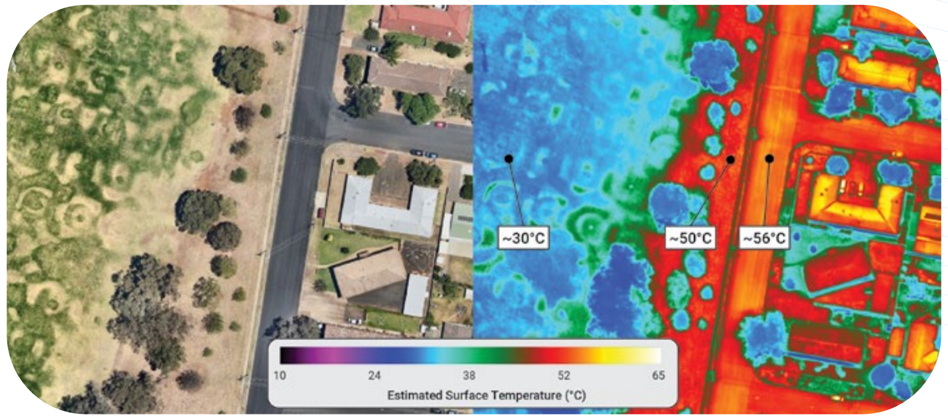

Figure R-2. Surface temperature of irrigated and unirrigated grass at South Dubbo Oval on a hot day (UNSW High Performance Architecture).

Apply Cool and Permeable Surfaces for Streets and Paved Areas

Although the low-density case study precincts of Maitland and Dubbo have higher proportions of pervious surfaces, the application of cool materials for roads, footpaths, and private hard surfaces provides surface and air temperature reductions during extreme heat events. In town centres, retail precincts, and higher-density residential areas in Maitland and Dubbo that require higher proportions of impervious surfaces, the cooling potential of these cool materials can significantly increase. In addition to these cool materials with high albedo and high emissivity properties, permeable or water retention pavements can also provide effective cooling benefits for footpaths, driveways, shared parking areas, and public plazas. The CRC for Low Carbon Living's 'Guide to Urban Cooling Strategies' (p.18) provides eleven common cool and permeable paving technologies, which includes their appropriate use in the public and private domain, and the key issues to consider in their application. Additional key considerations for applying cool and permeable materials for roads, footpaths, and private hard surfaces are provided below.

- High albedo and high emittance concrete and asphalt used in roads and footpaths should be designed to minimise the negative effects of glare on users of the public realm[28, 67].
- Conventional construction materials should include a higher proportion of lighter aggregates, additives, pigments, and binders (fly ash, slag, chip and sand seals, reflective synthetic binders)[67]. This can have the added benefit of reducing the embodied carbon emissions associated with roads and footpaths.
- When replacing existing roads and pavements is not an option, light-coloured coatings can be applied. Options include (1) high white coatings, (2) infrared reflective coatings, (3) heat reflecting coatings to cover existing asphaltic pavements, (4) colour changing coatings, and (5) fly ash, slag and recycled industrial by-products as aggregates of concrete pavements[67]. CoolSeal is a popular option for existing roads.
- The application of permeable pavements must consider the associated soil type and hydrogeological landscape, particularly for areas with salinity issues and low permeability. For soil types suitable for permeable paving, consider their application through (1) water holdings fillers as additive to porous asphalt, (2) fine texture pervious mortars as additive in pervious concrete, (3) fine blast-furnace powder in water retentive asphalt, (4) narrow particles of fly ash in bricks, (5) bottom ash as additives in pervious concrete, and (6) industrial waste as raw materials in ceramic tiles[67].
- Consider the application of thermochromic materials (intelligent coatings developed with nanotechnology) that enhance the thermal and optical properties of surfaces (reduced glare effect on pedestrians)[68].
- Limit the use of exposed synthetic turf due to their incredibly high surface temperatures on hot days (Figure R-3). Synthetic turf can be popular for residential areas for low-maintenance gardens as well as in playgrounds in parks, schools, and early learning centres, which can be a significant health hazard for children. However, a range of emerging synthetic turf products with increased surface reflectance and water retention properties could be considered when synthetic turf is needed (e.g. sporting fields), such as COOLplus™ [69].

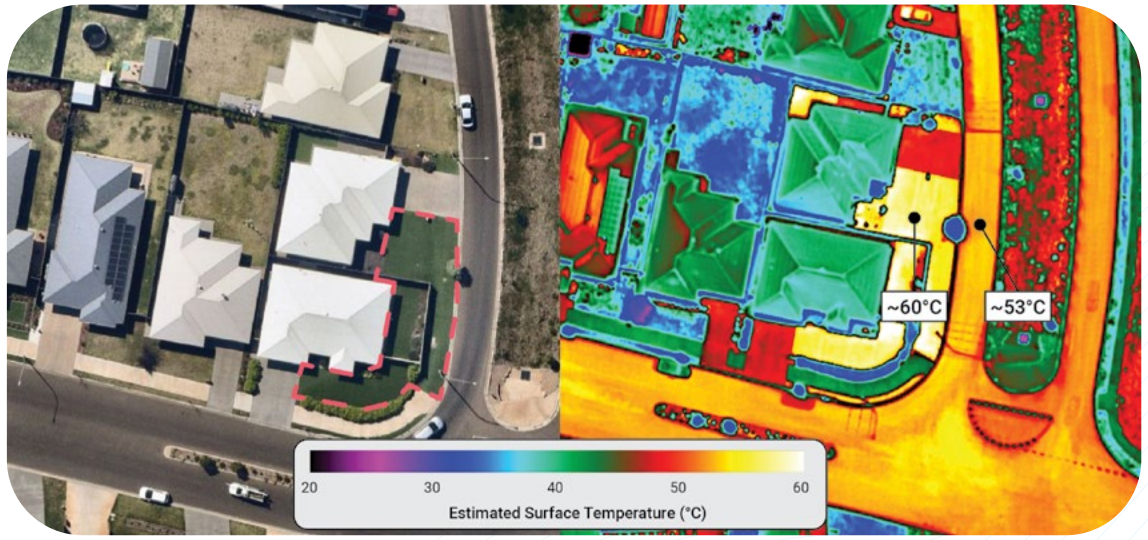

Figure R-3. The surface temperature of exposed synthetic turf in place of grass can be far hotter than dark asphalt roads during extreme heat events (UNSW High Performance Architecture).

Prohibit Dark Roofs for New Developments

There is substantial scientific evidence showing that dark roofs can exacerbate the urban heat island effect, severely degrade indoor thermal comfort, and increase peak and total cooling energy consumption during extreme heat events[25, 68, 70]. The case study results of the Maitland and Dubbo case study precincts in this report support these findings. Despite this, most new detached homes in Maitland, Dubbo, and many other cities across Australia, have a close affinity with dark-coloured roofs, whether that be for aesthetics, availability of roofing products, or other reasons. It is recommended that dark roof materials be prohibited for any new development or major renovation in Maitland and Dubbo. Researchers from UNSW's HPA Research Cluster have conducted a comprehensive cost-benefit analysis of applying cool roof technologies for different building types across Australia, which outlines their key benefits, limitations, and future developments. A cool roof is a roof with high solar reflectance and high thermal emittance (Figure R-4). One of the key barriers to the implementation of cool roofs is a lack of supportive policies and standards[25]. Some of the key considerations for developing such supportive policies for Maitland City Council and Dubbo Regional Council are shown below.

- Minimise the use of dark-coloured, low solar reflectance, and low emittance materials (e.g. dark-coloured concrete or tiles); unless 'smart' materials (which can reflect in the near-infrared/infrared) are used[68, 70].
- Encourage the construction of roofs with high emissivity, high albedo and low heat conductivity but should be designed to minimise the impacts of undesirable glare (e.g. where the roof is highly prominent to other building occupants or to those in public spaces)[28, 68, 70].
- While there is no standard strictly defined limit for solar reflectance for cool roofs, it is recommended that flat or low-sloped cool roofs have an initial solar reflectance greater than 0.65 and thermal emittance greater than 0.80[25].
- Consider defining performance standards for Solar Reflective Index (SRI) values for roof materials in relevant planning policies such as DCPs[65]. This could be supported by a recommended product library of cool roof materials or colours such as Colorbond's Coolmax® steel or steel cool roofing colours.
- For heritage buildings or other situations where replacing existing roof materials is not feasible, consider the use of white or light-coloured coatings[28, 67].
- More advanced cool material technologies such as daytime radiative cool materials, coloured cool materials, and retroreflective materials may also be considered once commercialised products are available[25]. These advanced cool roof material options can address the challenges of excessive glare and colour flexibility for aesthetic or heritage purposes.
- Cool roofs may cause heating load increases, especially in colder climates, and factors such as local energy prices should be considered to determine if a cool roof is a cost-effective solution. However, optimising roof albedo in combination with insulation levels for specific climatic conditions and buildings can cost-effectively reduce energy consumption for heating and cooling[25].
- Consider the durability of cool roof materials from weathering, soiling, biological growth, and chemical and physical stress. The accumulation of soot (black carbon), which is prevalent in polluted areas or after bushfires can also impact the solar reflectance capabilities of cool roofs[25].
- Advocate for cool roof materials and their benefits with developers, builders and homeowners.

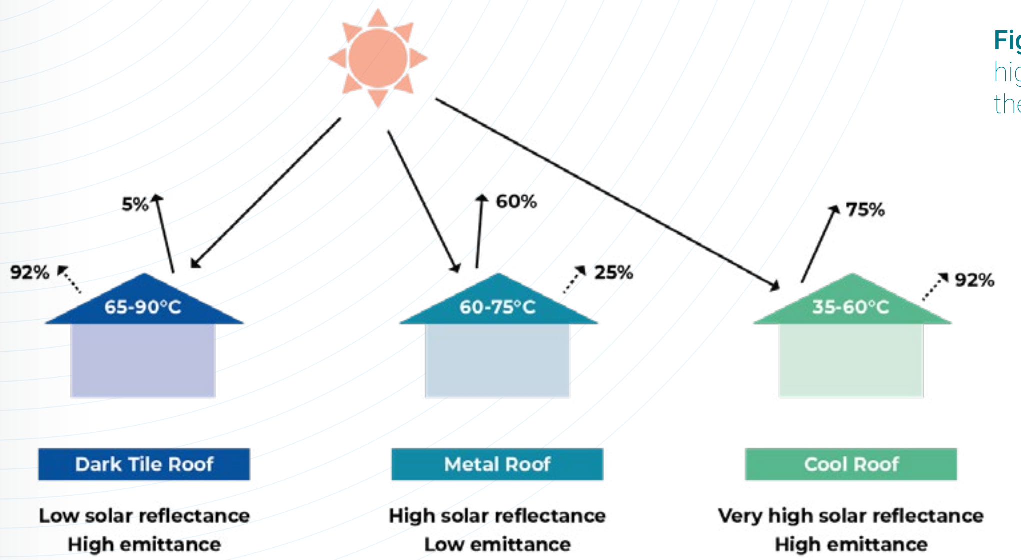

Figure R-4. A cool roof has high solar reflectance and high thermal emittance properties[28].

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Maintain and Encourage Shading and Water Misting Along Key Pedestrian Routes

Outdoor shading structures and evaporative cooling technologies such as water misting systems can provide much needed relief during extreme heat events. The cooling potential analysis results from the case study precincts in Maitland and Dubbo showed significant air and surface temperature reductions from the addition of outdoor shading and water misting sprays. As these cooling benefits are localised, the location and design of outdoor shading structures and misting sprays should be carefully considered to maximise their effectiveness for identified hot spots. Maintaining and encouraging outdoor shading and water misting along key pedestrian routes is therefore recommended for Maitland and Dubbo. Some of the key considerations to do so are shown below.

Outdoor Shading Structures:

- Shading devices should be prioritised in overexposed street canyons (wide streets and footpaths, boulevards, pedestrian streets) and open spaces (plazas, squares, parks, playgrounds) with high pedestrian activity[28].
- Shading devices and technologies that could be implemented include arbours, pergolas with climbing plants (trained vines), fixed, temporary or movable shading devices, integrated translucent PV panels, tension membrane structures, etc.[28, 71].
- Outdoor shading devices should consider cool roof materials while ensuring that the negative effects of glare are minimised for those within the public realm. Shading devices may also consider integrating rainwater harvesting and evaporative cooling systems like misting sprays, provided it is not in a humid climate[23, 28] (Figure R-5).
- Fixed and retractable awnings of sufficient width (at least 3.5m) and height (3.5-4.5m) should be maintained and encouraged along active streets (and especially north-facing footpaths) to reduce solar exposure of surfaces, minimise solar penetration into buildings' ground floors and as weather shelters (i.e. rain, wind)[62].
- Consider the use of non-continuous awnings or with steps ups and breaks to promote air flow.
- Audit existing bus stops to identify those without adequate shading for pedestrians. This is particularly important for people who do not own or have access to private vehicles during extreme heat events. A comprehensive crowd-sourced audit of Sydney's bus stops was conducted by Sweltering Cities between 2022 and 2024.

Evaporative Cooling Systems:

- Consider utilising passive and active evaporative cooling systems strategically in public places. Passive systems include the provision of tree plantings and water features (fountains, lakes, ponds, rivers, etc.), while active systems correspond to evaporative/refrigerate air-conditioners such as multistage evaporative coolers, fine water sprays, and misting fans (with or without induced air velocity)[28, 63].
- The intensity of cooling effects provided by water features can be controlled by modifying the depth and extent of water. That is, larger, deeper water bodies will provide a greater cooling potential[63].
- Consider regular streetscape irrigation and pavement watering systems (i.e. surface running water) in the design or retrofit of public open spaces and streets. However, these should not be utilised in humid climates as this could result in increased relative humidity and decreased outdoor thermal comfort[23, 28, 63].
- Where water supply infrastructure cannot be supplied or is too expensive, encourage smaller scale creative solutions such as micro-mist spraying systems mounted on urban transportation (buses) in dense urban areas[72].

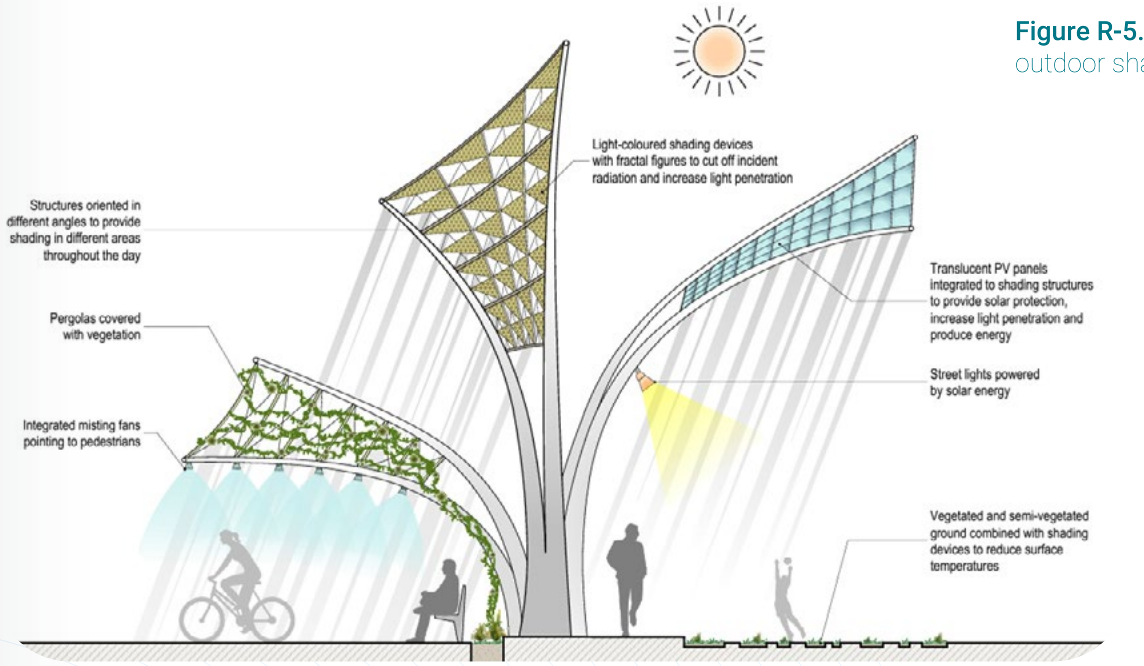

Figure R-5. Different types of outdoor shading structures[28].

Increasing Housing Density Must Integrate a Combination of Mitigation Strategies

The cooling potential analysis results from the case study precincts in Maitland and Dubbo clearly show that a combination of heat mitigation strategies is the most effective way to limit precinct-wide urban overheating. Importantly, the subdivision scenario analysis results for Southlakes in Dubbo demonstrate that increases in density from the traditional 600 m^2 residential lot size will likely result in exacerbating urban overheating unless a comprehensive combination of mitigation strategies is integrated. This has implications for future development in Maitland and Dubbo, especially given the housing crisis, the need for affordable housing, and continued post pandemic population growth outside of the major cities in Australia.

Therefore, it is strongly recommended that future higher-density development in these cities carefully consider an appropriate combination of heat mitigation strategies early in the design phase. The recommendations above can provide a starting point for establishing an effective combined heat mitigation strategy. While it is an emerging field, there are tools being established to support local councils, urban planners, and developers to create and test different heat-resilient scenarios. Some of these include (each with their own specific benefits and limitations):

- Microclimate and Urban Heat Island Mitigation Decision-Support Tool (UHI-DS) developed by UNSW's HPA Research Cluster and the CRC for Low Carbon Living Australia (Figure R-6).
- The Cool Suburbs Tool developed by the Western Sydney Regional Organisation of Councils (WSROC), Resilient Sydney, and Greater Sydney Commission.
- Water Sensitive Cities Scenario Tool developed by the CRC for Water Sensitive Cities.
- UHeat developed by Arup, University College London, and University of Reading.

Figure R-6. The UHI-DS Tool developed by UNSW's HPA Research Cluster showing cooling intervention scenarios in South Melbourne

Establish a Network of Community Heat Refuges

Heat refuges can play a critical role in strengthening a local community's adaptive capacity to extreme heat, especially for those who are more vulnerable. Community heat refuges are typically air-conditioned facilities such as libraries, halls, shopping centres, and cinemas, but can also include public outdoor spaces like swimming pools (Figure R-7). With projected increases in the frequency and severity of heatwaves, the rising cost of electricity to run air conditioners, and the risk of blackouts, it is important that the local community have places of relief to extreme heat that are accessible to all. It is recommended that Maitland City Council and Dubbo Regional Council establish a network of community heat refuges. Some of the key considerations for community heat refuges are shown below.

Figure R-7. The Tregear Community Centre in Blacktown City Council was one of the first buildings in Australia established as a 'cool centre' or heat refuge (Image: Kelsey Sanborn).

- Heat refuges should be prioritised in locations where populations are highly vulnerable to extreme heat events (see Report A), especially in lower income communities where constant air conditioning cooling cannot be afforded[73, 74].
- Heat refuges should be easily accessible and strategically spaced to allow young and elder people to rest, cool, and recover during extreme heat events. These areas should enable physical adjustment to heat using either passive or active cooling systems, while supporting incidental social activities[73, 74].
- Additional special-purpose heat refuges for emergencies may be required during prolonged periods of extreme heat[73, 74].
- Consider transportation routes to and between heat refuges during extreme heat events, especially for those who do not own or have access to private vehicles (e.g. shuttle bus services).
- Consider resilience principles for the design and operation of heat refuges. For example, the Living Building Challenge requires buildings to store a week's worth of drinking water for all regular building occupants at any given time from onsite water storage. Independent renewable energy generation and storage for heat refuges is also crucial during heatwaves with increased risk of blackouts.

Enhance Heat Education, Awareness, and Preparedness

Knowing what to do, where to go and how to cope can significantly increase a local community's capacity and capability to adapt and survive extreme heat events. While the NSW State Government and Bureau of Meteorology (BOM) have online resources available to support this, local governments can play a crucial role in translating this higher-level information into specific community action. It is therefore recommended that community heat education, awareness, and preparedness are enhanced through targeted strategies, initiatives, or campaigns. Some of the key recommendations to support this aim are shown below.

Figure R-8. Example of the City of Melbourne's cool routes platform (Image: City of Melbourne).

- Local governments should identify and monitor their most vulnerable communities and prioritise heat education initiatives in these areas.
- Consider establishing a comprehensive set of online resources to support the community's understanding of extreme heat and how they can be best prepared for extreme heat events. These might include:
  - Heat-adaptive and resilient behaviours at home (e.g. precooling using air conditioning, closing all blinds and windows, operating ceiling fans, checking on your neighbour, etc).
  - An interactive map of all community heat refuges in the local government area and how busy they are during extreme heat events.
  - Establishing 'cool routes' for active transport during extreme heat events. For example, the City of Melbourne have established an online portal for cool walking and cycling routes, which shows the location of all drinking fountains and green and blue infrastructure (Figure R-8).
  - Online or phone-based heatwave warning systems based on the BOM Heatwave Service so that community members are aware of the predicted length and severity of upcoming heatwaves.
- Advocating for energy and water service providers to provide financial incentives for conserving and managing electricity and water consumption during extreme heat events to help relieve stress on supply systems.
- Establish policies to manage and schedule events such as sport games, festivals or public gatherings during summer in a way that impacts of heat on participants is minimised. Strategies include scheduling events during the late afternoon or evening, provide sufficient shade and water bottle filling stations, and providing heat refuges and continuous emergency support.

The Role of Local Government

In designing and maintaining heat-resilient cities, local governments are the critical interface between local communities and the development industry. Planning policies such as local environmental plans (LEPs) and development control plans (DCPs) enable opportunities to directly improve urban heat outcomes for new developments and the redevelopment of existing areas or buildings. However, it is worth acknowledging there are many alternative development pathways (e.g. state-significant developments, exempt and complying developments) and planning instruments (e.g. BASIX) that can override local policies despite their best intentions[65]. Regardless, there are many opportunities to enhance urban heat provisions in LEPs and DCPs. The key findings and recommendations from Phase 1 of the NaHVO provide a strong foundation for Maitland City Council and Dubbo Regional Council to do so.

Directions for Phase 2 Work

Phase 1 Summary: Development of the National Heat Vulnerability Observatory's Foundational Elements and Methodology

The NaHVO Phase 1 aims to support the delivery of smart, cool, and resilient places by establishing an innovative, robust and consistent approach to measuring and reporting heat vulnerability, which integrates mitigation and adaptation strategies to capture the potential to reduce heat vulnerability. Maitland City and Dubbo Region were pilot cities for Phase 1 of the NaHVO.

Phase 1 of the NaHVO has established:

- **NaHVO benchmark datasets** to provide the ability to monitor heat vulnerability tailored to specific urban contexts and local overheating issues.
- **Performance measures and key indicators** built upon NaHVO benchmark datasets to establish a consistent methodology for heat vulnerability assessment.
- **Analytical modelling for cities and precincts** with what-if scenario analysis of mitigation and adaptation interventions to investigate the cooling potential of cities and precincts.
- **Data interoperability** to provide data collection protocols, including data categories, sources and processes, which are repeatable to establishing NaHVO benchmark datasets for more cities in Australia. It has also established a feasibility study of connections to government platforms using the NSW Digital Twin platform as an example.

The key features of the NaHVO that make it innovative and unique are:

- **A nationally consistent and robust approach to measuring and reporting urban heat vulnerability issues**, which can be applied to more cities in Australia.
- **An expanded scope that defines diverse key performance indicators to measure the heat vulnerability performance of cities or precincts**. The NaHVO Index encompasses not only the heat-related impacts on population health but also the effects on the thermal environment and energy consumption. Additionally, it includes in-depth built environment characteristics along with other key influential factors, which inform cooling intervention opportunities. It identifies the relationships between the key influential factors and key performance indicators through statistical analysis methods and regression models, built upon NaHVO benchmark datasets and evidence.
- **An ability to link mitigation and adaptation strategies with the NaHVO Index**, which enables the representation of the effectiveness of cooling interventions as potential changes in heat vulnerability to support decision-making. This is supported by modelling and simulations of what-if cooling potential analyses. Additionally, real-time NaHVO benchmark datasets and the future application of artificial intelligence techniques will enable monitoring and predicting how heat vulnerability changes or could change over time.
- **A smart data-driven approach that provides a central NaHVO data repository** to support smart data analysis and interoperability and enable to the incorporation of artificial intelligence techniques into NaHVO in the future. This increases digital capability in urban cooling to adapt to future smart cities.

The NaHVO Phase 1 Smart and Cool Places in NSW project enhances a digital capability in NSW to increase the state's resilience to urban overheating. It provides potential key benefits to government, planners, developers, designers, and communities as follows.

Government

- Adopt a holistic approach to measuring and reporting heat vulnerability of cities and precincts, covering thermal environment, human health, and energy consumption impacts.
- Develop scientific and evidence-based effective mitigation strategies tailored to the local built environment characteristics to reduce heat vulnerability.
- Prioritise heat vulnerability investments.
- Monitor the heat vulnerability performance of cities and precincts over time with support of 3D interactive government platforms.

Planners, Developers, Architects, and Designers

- Establish specific heat mitigation planning controls and design requirements.
- Estimate the effectiveness of urban and building mitigation interventions for specific locations.

Communities

- Understand heat vulnerability conditions that will help make decisions about where to live and what can be done to adapt to extreme heat.

Phase 2 Scale-Up of the NaHVO

Government User Needs Workshop

The next step in the NaHVO's development will be a scale up to integrate more cities in NSW and across Australia. A 'Government User Needs Workshop' was conducted in May 2024 to understand business needs, heat mitigation strategies of interest, required data and functionality, stakeholders, and key challenges. The outcomes of this workshop will inform and scope the scale-up plan for Phase 2 of NaHVO development.

The objectives of this workshop were to inform the development of an operational system that can be scaled and used by governments, researchers, and industry organisations across Australia. It aimed to identify specifically how the NaHVO would be used by governments and to identify challenges that will need to be addressed.

The two-hour workshop was held virtually with participation by local, state, and territory government representatives, with a total of 43 participants. The relative proportions of local versus state and territory participants are shown in Figure S-1 (a), while the relative proportions by Australian state and territory participants are show in Figure S-1 (b).

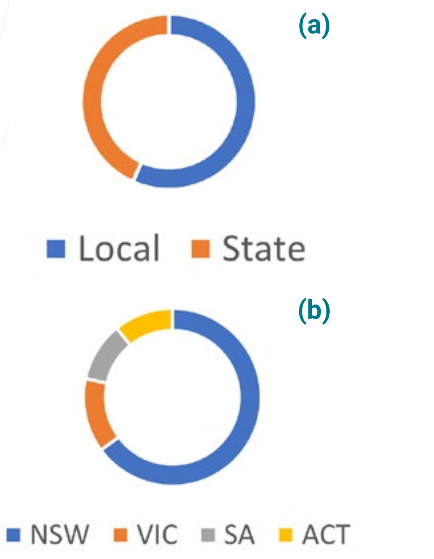

Figure S-1. (a) The relative proportions of local versus state and territory participants, and (b) the relative proportions by Australian state and territory participants.

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Table S-1 outlines the required functionality recommended by the workshop participants, which falls into six areas: modelling, analysis, reporting, supporting collaboration, community engagement and others. Table S-2 introduces the challenges that will need to be addressed.

Table S-1. The required functionality recommended by the workshop participants.

AREAS	REQUIRED FUNCTIONALITY
Modelling	» Modelling to support advocacy of changes to state planning policies » Testing common assumptions about impact of wind direction and strength on heat » Modelling costs of proposed mitigation » Understanding heat vulnerability under different scenarios » Tree canopy coverage modelling and optimising coverage per $ spent » Measuring aggregated effects of different cooling methods (cool roof + tree canopy cover + permeability) – modelling different % of each » Define "vulnerable households" to help identify which data source to use
Analysis	» Mapping tree canopy cover to heat vulnerability » Understanding how building temp and comfort change during the day » Optimise street and park tree planting positions » Understanding trade-offs between urban densification and green space development
Reporting	» Reporting on land development KPIs » Reporting actual number of high heat days vs predicted number » Include non-financial indicators such as lives lost, hospital presentations, work days lost » Correlating real-time heat data with energy consumption » Data and benchmarking useful to evaluate effectiveness of interventions
Supporting collaboration	» Sharing best practises, what has worked and what hasn't » Needs to be easy to use by non-experts » Informing micro-climate assessments for development applications » Supporting different scenarios so that developers and governments can try different approaches/designs
Community engagement	» Needs to be easy to use by non-experts » Help community to see hotspots and heat refuges » Tools to help communities understand heat risks and how to keep cool at home » Ensuring citizens can benefit from heat data, indices etc
Others	» Need to be able to export datasets » Integration with ArcGIS, ESRI, etc

Table S-2. The challenges that will need to be addressed, which were introduced by the workshop participants

CHALLENGES	POTENTIAL SOLUTIONS
Understanding the data	» Easy to use dashboard(s) » Finding a way to show the relationships between different parameters / factors that impact heat in one place
Funding / Business Case	» Modelling would be useful to inform business cases for funding » Understand co-benefits to help with business case » Business case needs to be transparent » Funding officer to sit across multiple councils » Climate risk obligations becoming regulatory when considering masterplans » Driving adoption by linking to insurance industry
Sensitive data cannot be made public	» Implement public/private data access by organisation or role » Address potential privacy concerns from real-time sensors
Training will be required continually due to staff turnover in organisations	» Make it intuitive to use to minimise training cost » Specific training by user role
Integration with existing sources	» Integrate with NSW SEED » Integrate with GIS systems » Integrate with SA's spatial web app
Coordination across government departments and other organisations	» Ensure this feeds into NCC process. This will have the biggest impact on building performance. Need to drive ABCB integration » Undertake stakeholder gap analysis » Support multiple organisations working on the same scenarios
Encourage participation	» Be open with data sources to allow councils and others to contribute data

Directions for Phase 2 of the NaHVO's Development

Directions for Phase 2 of NaHVO development will consider user needs, innovation, intermedium production, and final production. The following five areas will help to scope Phase 2 of NaHVO development.

Intermedium Production of Australia National Heat Vulnerability Observatory Benchmark Datasets

This includes expanding the scope of the NaHVO benchmark datasets, both geographically and by including additional key performance indicators such as outdoor air quality, UV data, and water consumption, along with diverse risk factors. Intermedium production of NaHVO benchmark datasets will be accessible via an application program interface (API) for data query and connections to various applications to support urban policy and planning decision-making in reducing heat vulnerability.

NaHVO Index in More Cities in Australia

Scaling up to cover more cities could require groupings based on built or urban typologies. Built or urban typologies will be further developed and integrated into the NaHVO Index while involving more cities in NaHVO Index.

This involvement will enrich the evidence of the relationships between heat vulnerability key influential factors and key performance indicators, thereby making the NaHVO Index more robust. It will enhance the evidence-based reporting of how local heat vulnerability profiles (heatwaves, built environment characteristics, and socio-demographic characteristics) contribute to heat vulnerability performance indicators (outdoor thermal environments, heat-related mortality and morbidity, and energy consumption).

Further research on how integrating mitigation strategies can affect heat vulnerability will be conducted, particularly analysing heat-related morbidity and mortality impacts. This requires the support of experts in public health. Additionally, a range of adaptation strategies can be integrated into the NaHVO Index.

Connections to More Government Platforms

NaHVO repository and connections to more government platforms and various applications can be further developed. This involves automated processes and methods for connections, and API access for the automated importation of data from NaHVO Repository, including real-time sensor data. Additionally, 3D visualisation of what-if scenarios of mitigation and adaptation strategies and their impacts can be implemented on government platforms or a standalone platform to support decision-making and monitor heat vulnerability reduction over time.

Development of Artificial Intelligence (AI) and Machine Leaning Techniques for Data-Driven Decision-Making in Urban Heat Mitigation and Adaptation

Advanced artificial intelligence (AI) techniques can be integrated into Phase 2 of NaHVO development, such as the application of neural network and machine learning methods to NaHVO benchmark datasets. Neural network methods can train the relationships between key influential factors and key performance indicators related to heat vulnerability, while machine learning methods can help identify patterns, trends, and predict possible changes in urban heat risks resulting from mitigation and adaptation strategies.

Additionally, an evidence-based casual-effect network can be established based on rich case studies and literature, and then integrated with a Bayesian network to provide probability analysis of the effectiveness of various mitigation and adaptation strategies without simulations. This approach will complement modelling and simulation methods.

Providing Production Services, Repeatable Processes, Training, and AI Automation of the Process

Finaly, it is crucial to establish more repeatable and consistent processes for processing data to speed up the scale up of the NaHVO index. Additionally, training will be provided to enhance the usage of the NaHVO in support of monitoring, planning, and implementing cooling interventions.

Future iterations of the NaHVO can be open to communities, allowing residents to see hotspots and heat refuges, understand heat risks and the cooling potential of their locations, and adapt to heat extremes. Such community engagement can help governments and residents create smart, cool, resilient, and liveable spaces.

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Appendix

Appendix 1 – The Parameters for Urban Greenery in the Mesoscale Simulation Model

The table below lists the parameters for urban greenery in the simulation model at the mesoscale. The green vegetation fraction indicates the proportion of the total green space area that is covered by vegetation. The other parameters relate to the physiological and physical characteristics of vegetation, which influence the density of evapotranspiration.

Parameter	Mixed vegetation of shrub/grass/ trees	Evergreen broadleaf trees	Parameter	Mixed vegetation of shrub/grass/ trees	Evergreen broadleaf trees
Green vegetation fraction [fraction 0-1]	0.8	0.95	Maximum leaf area index through the year [dimensionless]	2.26	6.24
Average root depth/[soil layer index]	3	4	Minimum background roughness length through the year [m]	0.92	0.95
Stomatal resistance [s/m]	40	150	Maximum background emissivity through the year [fraction 0-1]	0.98	0.95
Adjusting coefficient used in radiation stress function	100	30	Minimum background albedo through the year [fraction 0-1]	0.18	0.12
Adjusting coefficient used in vapor pressure deficit function	36.25	41.69	Maximum background albedo through the year [fraction 0-1]	0.23	0.12
Minimum leaf area index through the year [dimensionless]	0.38	3.85	Minimum background roughness length through the year [m]	0.15	1.03
Maximum background roughness length through the year [m]	0.15	1.03			

Appendix 2 – Cooling Potential at a Mesoscale in Maitland City

The figures below present the cooling potential at a mesoscale in Maitland City resulting from mitigation strategies. They include the range of air and surface temperature reductions during the two heatwave periods from WRF simulations.

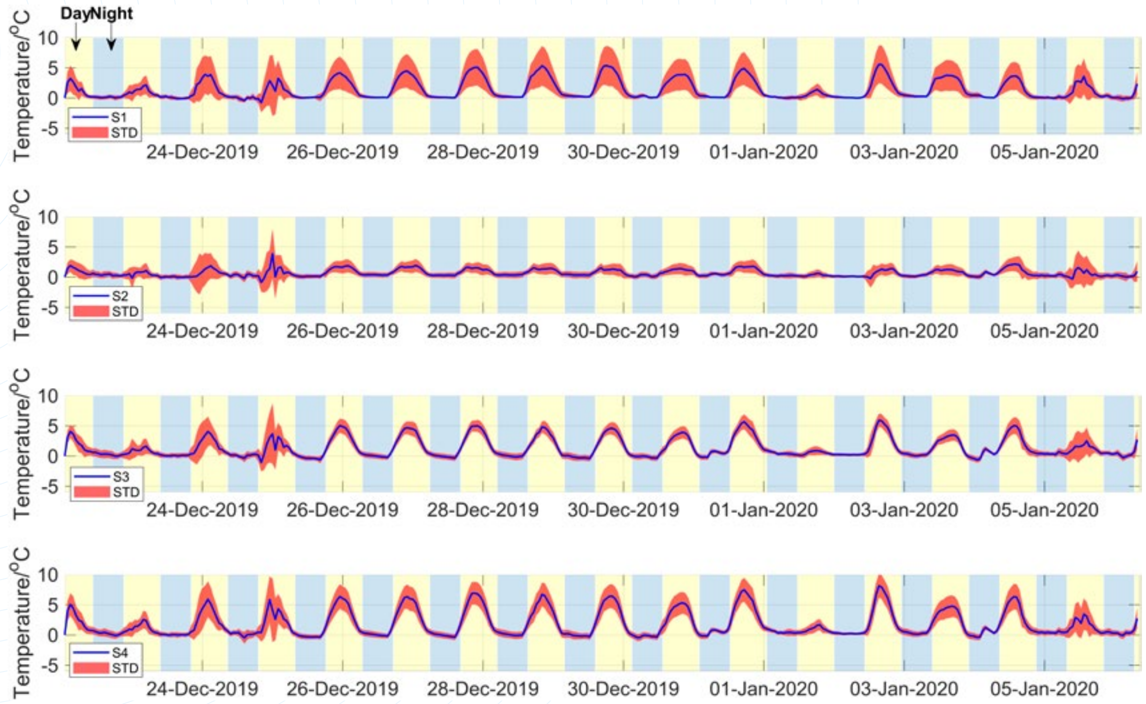

Figure X-1. Surface temperature reduction at a mesoscale in Maitland City during the first heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

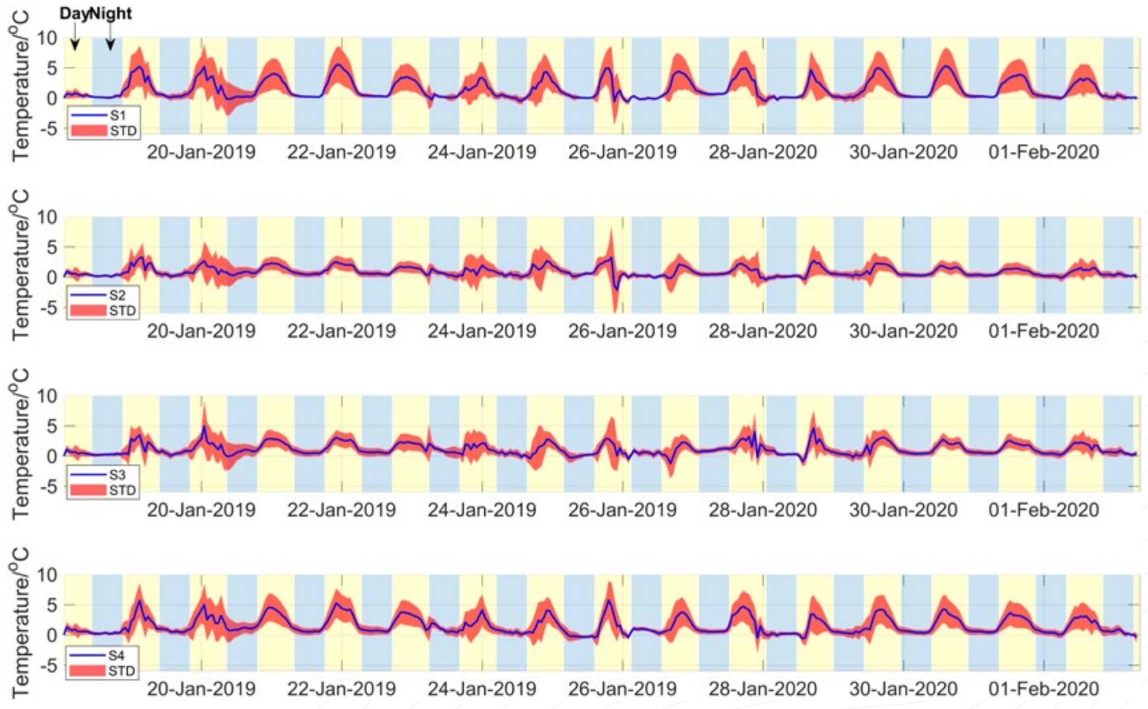

Figure X-2. Surface temperature reduction at a mesoscale in Maitland City during the second heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

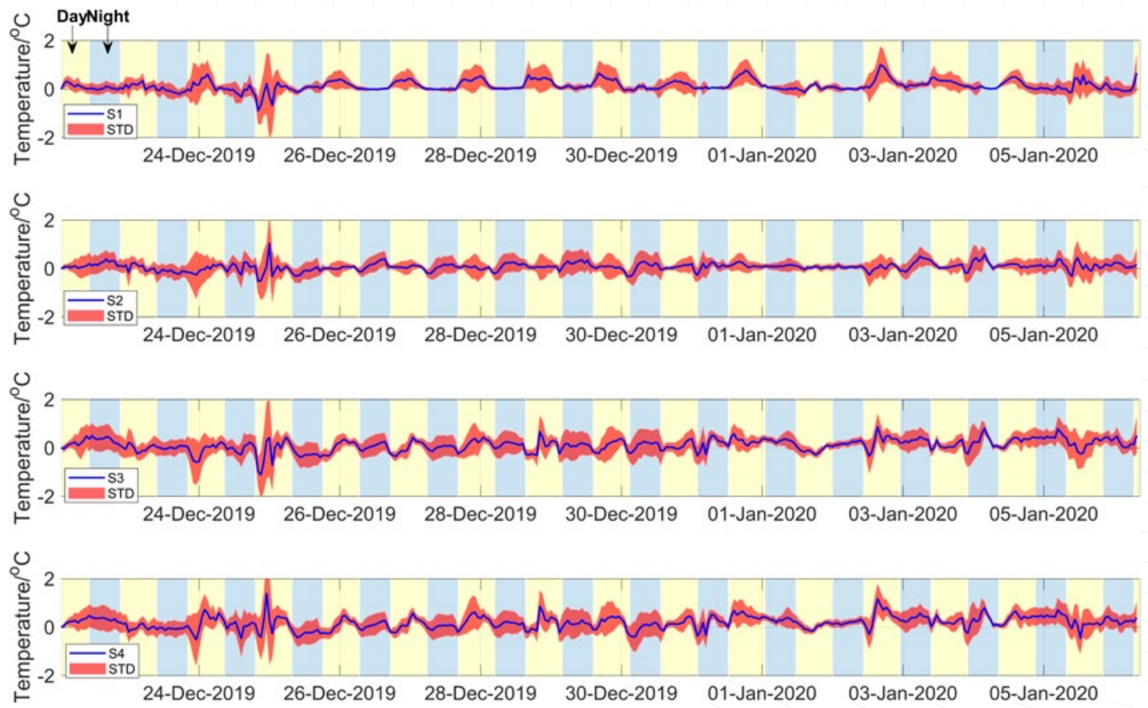

Figure X-3. Air temperature reduction (at 2 m) at a mesoscale in Maitland City during the first heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

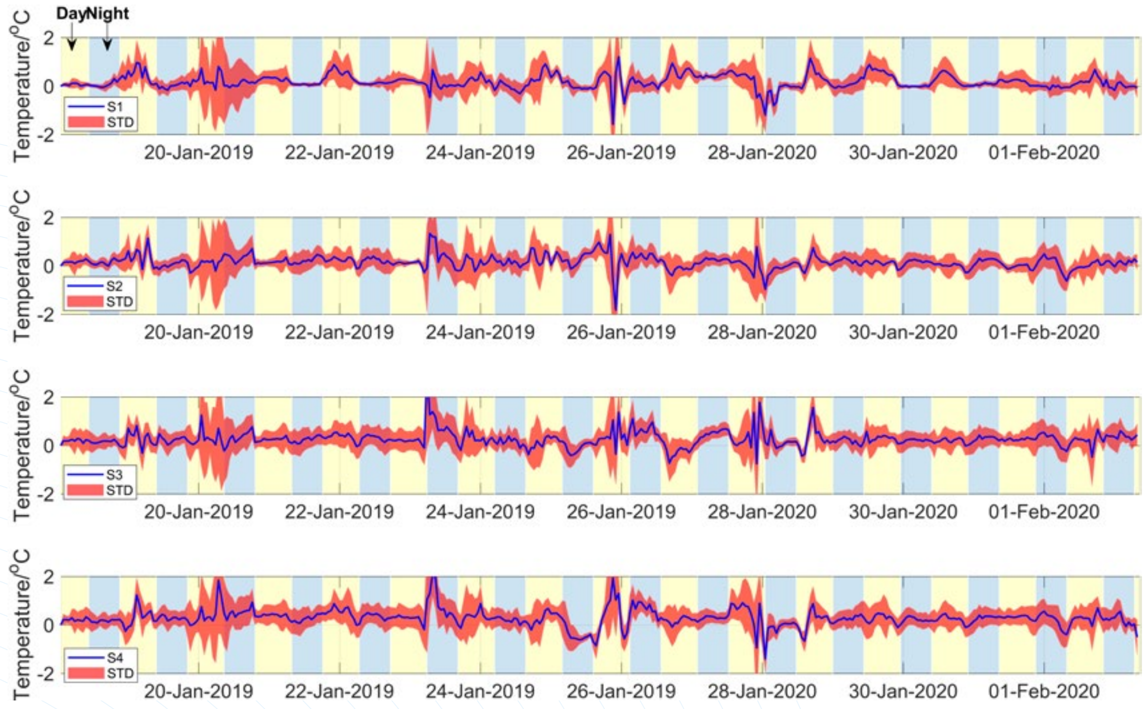

Figure X-4. Air temperature reduction (at 2 m) at a mesoscale in Maitland City during the second heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

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Appendix 3 – Cooling Potential at a Mesoscale in the Dubbo Region

The figures below present the cooling potential at a mesoscale in the Dubbo Region resulting from mitigation strategies. They include the range of air and surface temperature reductions during the two heatwave periods from WRF simulations.

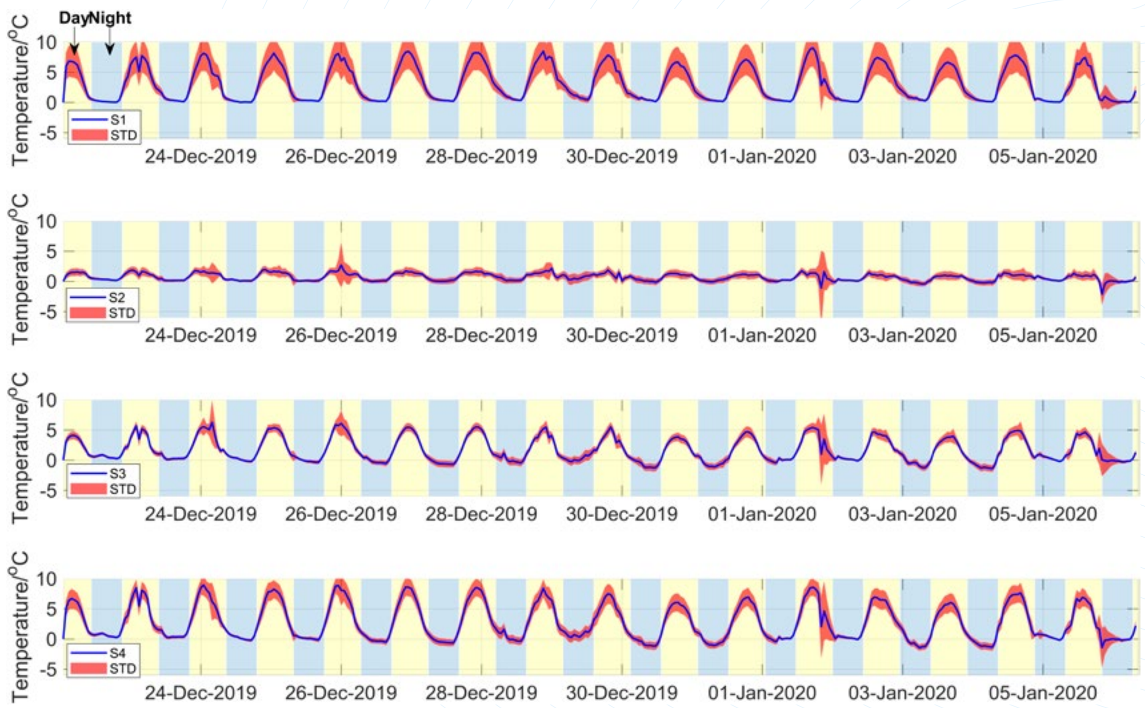

Figure X-5. Surface temperature reduction at a mesoscale in the Dubbo Region during the first heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

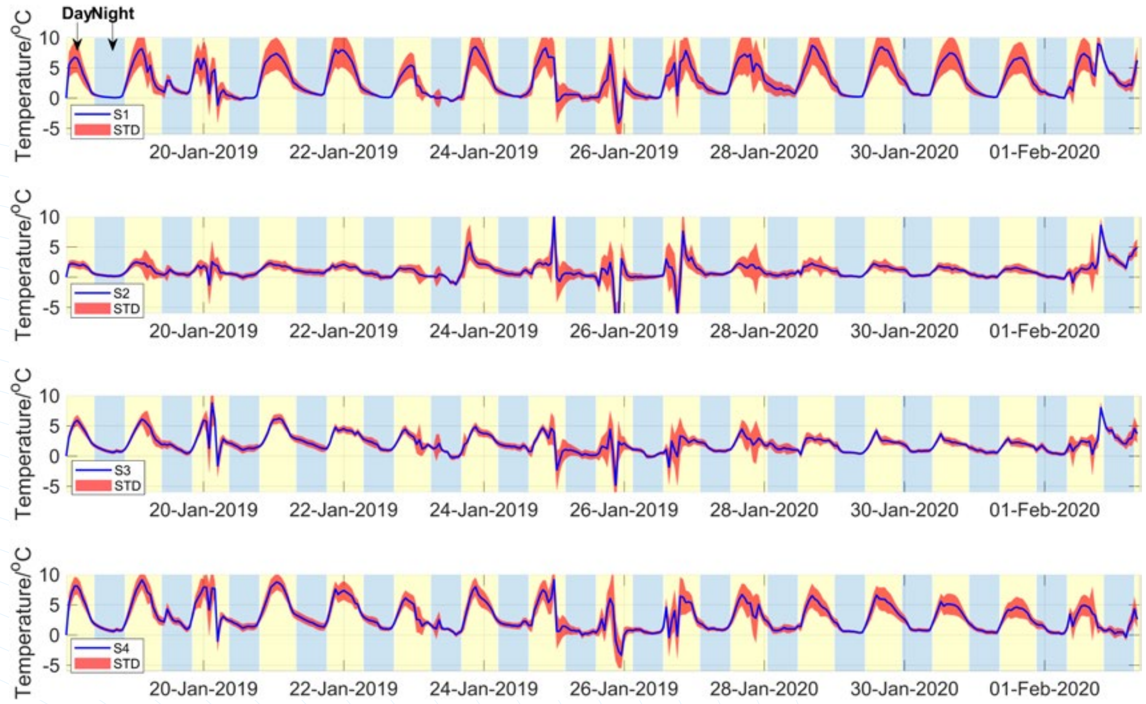

Figure X-6. Surface temperature reduction at a mesoscale in the Dubbo Region during the second heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

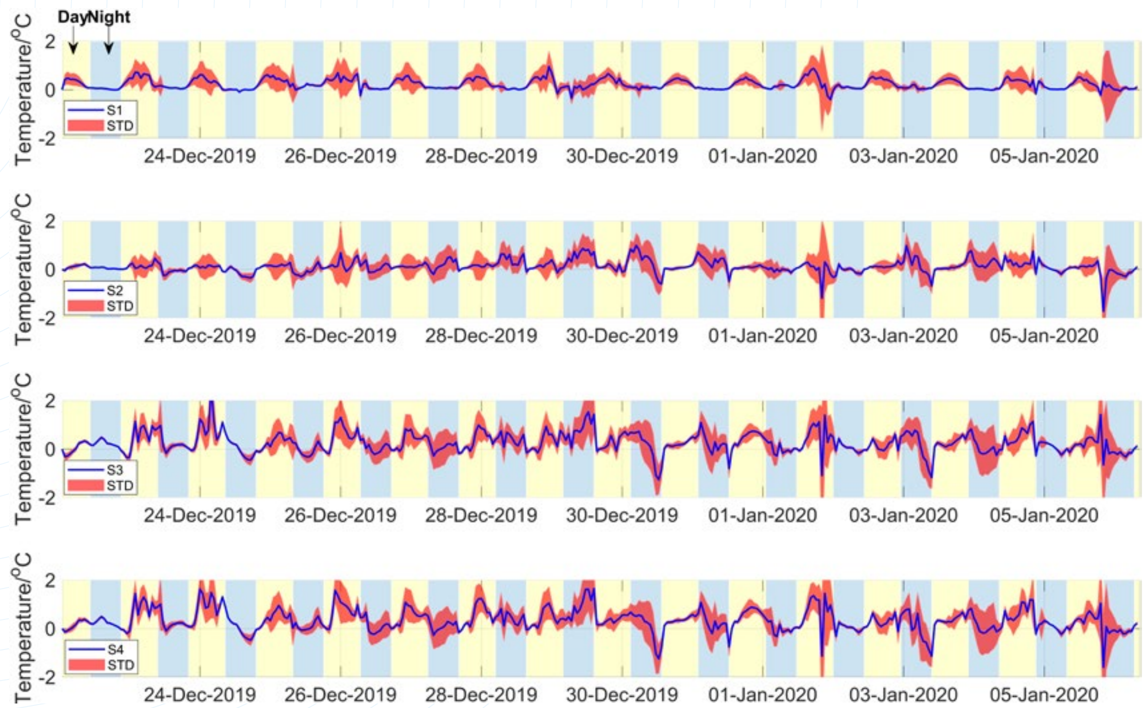

Figure X-7. Air temperature reduction (at 2 m) at a mesoscale in the Dubbo Region during the first heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

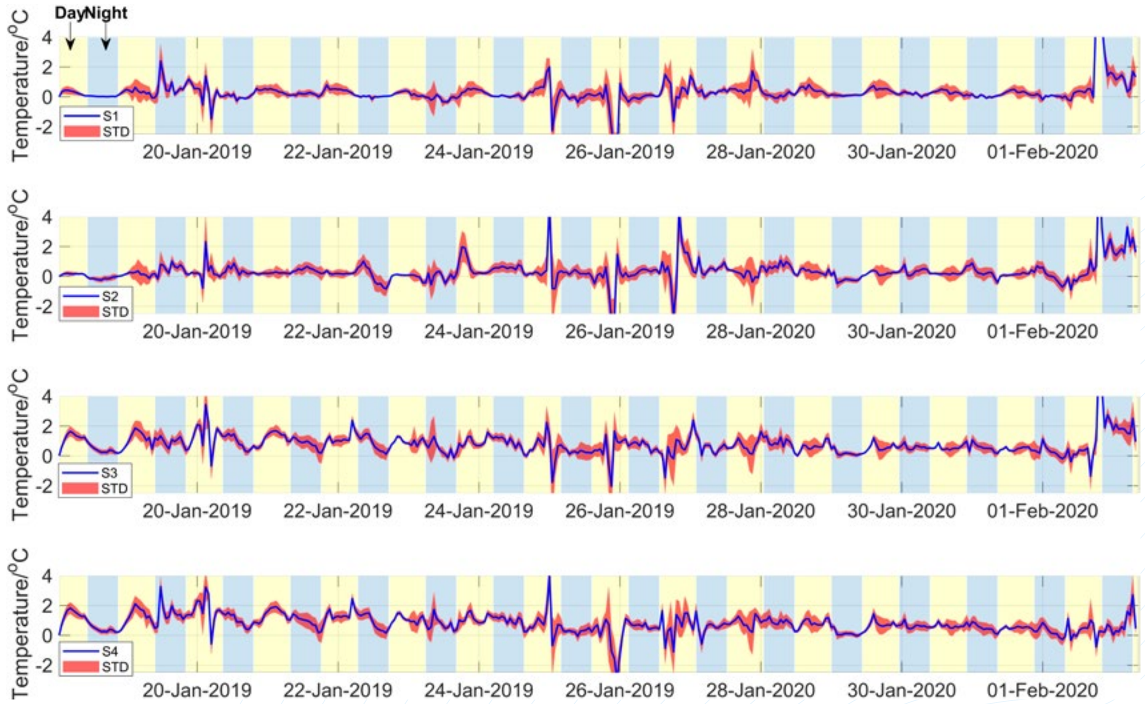

Figure X-8. Air temperature reduction (at 2 m) at a mesoscale in the Dubbo Region during the second heatwave period resulting from mitigation strategies, where S1: Cool materials, S2: Greenery, S3: Greenery with water irrigation, and S4: A combination of all these mitigation strategies. The shaded area in orange represents the range of the reduction, which is the Standard Deviation (STD) of temperature reduction.

Appendix 4 – Data Specifications for the NaHVO Repository Structure

The tables below provide data specifications for the NaHVO repository structure as presented in Report D (refer to Figure D-2).

ABS Codes

This denotes a single ABS Statistical Area (SA). It could represent any SA level from SA1 to SA2; SA3 and SA4 are out of scope. It also includes the Local Government Area (LGA) name. If multiple LGAs are covered by a given SA code, then the LGA with the most area covered is given.

abs_codes_id	integer	Unique ID for entries in this table
lga_name	text	Name of LGA coving majority of SA region
sa_level	integer	ABS SA level
sa_code	text	ABS SA code
sa_year	integer	Release year for ABS SA region

Boundary

This denotes a geographic boundary for an ABS SA code. It has a one-to-one mapping to entries in the ABS Codes table.

boundary_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to ABS codes table
geometry	geometry	2D region boundary

Site

It represents a conceptual site defined as the union of multiple ABS SA areas. This could be used to represent a case study site.

site_id	integer	Unique ID for entries in this table
name	text	Name for the site

Site to ABS Code Map

There are multiple mappings between ABC levels, ABS codes, and case study sites. This table facilitates that linkage.

site_id	Integer	Unique ID for entries in this table
abs_codes_id_fk	Integer	Reference to the ABS codes table
site_id_fk	Integer	Reference to the site table

Heatwave Profile

This represents the heatwave profile for each ABS SA code and month. It represents the severity of an existing heatwave for the ABS code, and the duration of the heatwave.

heatwave_profile_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to the ABS codes table
month_year	datetime	Date time object with the month and year for each row
heatwave_category	text	BoM heatwave category assigned for this month and year
heatwave_length	integer	Length of the heatwave

Community Profile

The represents the socio-demographic data describing the community linked to each ABS SA area.

community_profile_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to the ABS codes table
population	integer	Population of the SA area
"Population < 4 & > 65"	integer	Percentage of population under 4 or over 65
"Living alone (>65)"	integer	Percentage of population living alone and over 65
"Year 12 completion"	integer	Percentage of population who have completed year 12
"Low income"	integer	Percentage of population defined as low income
"Socio-econic disadvantage (SEIFA-IRSD)"	integer	Index of relative socio-economic disadvantage (SEIFA-IRSD)
"LT Health conditions"	integer	Percentage of population with long term health conditions
"Need assistance"	integer	Percentage of population who need assistance with core activities
"Non-English speaking"	integer	Percentage of non-English speaking population

NaHVO Index

This represents the NAHVO Index values for each ABS SA code. Each entry contains a type corresponding to each key performance indicator (i.e. outdoor thermal environments, heat related mortality and morbidity, and energy consumption) and a value.

nahvo_index_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to the ABS codes table
Type	text	Type of NaHVO index (outdoor thermal environments, heat related mortality and morbidity, and energy consumption)
Value	real	Index value

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Health Data

This represents the heat related mortality and morbidity data linked to ABS SA codes. It comprises the number of admissions (heat-related morbidity or mortality) for a range of given dates and medical codes.

health_data_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to the ABS codes table
arrival_date	datetime	Date for this admission data
data_type	text	Type of admission
data_number	text	Number of admissions of this type
diagnosis_code	text	Medical code corresponding to a type

Electricity Data

It denotes monthly aggregate electricity usage data for ABS SA areas.

electricity_data_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to the ABS codes table
billing_type	text	Type of bill
monthly_electricity_use	real	Aggregate use for month
month_year	datetime	Month and year for this data

Built Environment

It represents a specific instance or design for a built environment. This may cover multiple SA areas which may or may not be defined as a single site. These may also represent the actual existing built environment for a given area (e.g. a “base case”) or a hypothetical built environment as part of a what-if scenario analysis.

built_environment_id	integer	Unique ID for entries in this table
abs_codes_id_fk	integer	Reference to the ABS codes table
name	text	Descriptive name for this built environment instance
typology	text	Typological name for this built environment
time_to_hospital	real	Average travel time to hospital from this built environment

Built Environment Object

It denotes a physical object in a built environment. In an object-oriented sense, this functions as a base class for subclasses such as public or private space objects. Each built environment object contains a geometry object. Every built environment object needs to be referenced by exactly one subclass table (i.e. built_environment_object_public_space, built_environment_object_private_space, or built_environment_object_building).

built_environment_object_id	integer	Unique ID for entries in this table
built_environment_id_fk	integer	Reference to the Built environment table
geometry	geometry	2D or 3D boundary for this object
green_factor	real	Green factor for this object (if relevant)
built_upon_area	real	Percentage of area that has been built upon (if relevant)

Built Environment Object Public Space

It represents the base class for public space built environment objects.

built_environment_object_public_realm_id	integer	Unique ID for entries in this table
built_environment_object_id_fk	integer	Reference to the Built environment object table containing the geometry for this object
object_type	text	Type of public built environment object represented
object_area_derived	real	Area of object (may be derived from the physical geometry referenced in the base class)
hard_ground_surface_sri	real	SRI if object is a hard surface
water_bodies_perc	real	Percentage of object covered by water bodies
water_misting	boolean	Does the object contain water misting
outdoor_shading	real	Percentage of outdoor area in object that is shaded

Built Environment Object Private Space

It represents the base class for private space built environment objects.

built_environment_object_private_realm_id	integer	Unique ID for entries in this table
built_environment_object_id_fk	integer	Reference to the Built environment object table containing the geometry for this object
object_type	text	Type of private built environment object represented
object_area_derived	real	Area of object (may be derived from the physical geometry referenced in the base class)
Material	text	Material used to construct object
construction_type	text	Construction type used for object (if relevant)

Built Environment Object Building

It represents the base class for private space building built environment objects.

building_id	integer	Unique ID for entries in this table
parent_building_id_fk	integer	Reference to the parent building (null if this building does not represent a sub-component (e.g. roof, wall) of a larger building
built_environment_object_private_realm_id	integer	Reference to the Built environment object private space table
material	text	Material used to construct object

Electricity Simulation

It represents the simulated monthly aggregate electricity usage data for ABS SA areas for a given built_environment scenario. A derived difference value is also optionally stored showing the difference between the simulated electricity usage and the actual electricity usage for the corresponding ABS SA area stored in the electricity usage table.

electricity_simulation_id	integer	Unique ID for entries in this table
built_environment_id_fk	integer	Reference to the Built environment table
month_year	datetime	Date time object with the month and year for each row
monthly_electricity_use	real	Aggregate electricity use for month
difference_derived	real	Difference between monthly_electricity_use and the base case scenario (if this is not the base case). It may be derived from separate entries.
type	text	Electricity use category being described

Sensor

It represents a sensor object at a point in space. This can be real (e.g. a HOBO sensor deployed in a case study precinct), or artificial (e.g. for simulated data as part of a what-if scenario analysis). Sensors can also be optionally linked to a built_environment_object if the data being recorded is to be linked to a physical object (e.g. a surface temperature).

sensor_id	integer	Unique ID for entries in this table
abs_codes_ id_fk	integer	Reference to the ABS codes table
built_ environment_ object_id_fk	integer	Reference to the Built environment object table
name	text	Sensor name
description	text	Description of sensor and location
location	geometry	Location coordinates for sensor
is_simulation	boolean	Whether or not this data describes real measurements or simulations

Outdoor Thermal Monitored

It represents outdoor thermal properties (see below) measured at a given point in space (represented by a sensor). As described above, this can be either a real measurement or a simulated one; the difference is denoted according to the "is_simulation" property of the linked sensor.

The thermal property being measured is indicated by the value of the type enumeration variable. Values include "air temperature", "surface temperature", "humidity", "wind speed", "thermal comfort", and "solar radiation".

outdoor_thermal_monitored_id	integer	Unique ID for entries in this table
sensor_id_fk	integer	Reference into the sensor table
type	text	Property being monitored
value	real	Value recorded
time	datetime	Timestamp for measurement

Outdoor Thermal Simulation

It represents thermal data linked to a climate simulation for a given what-if scenario (represented by a built_environment object). It contains a heatmap as well as a time (year, month, day, and time) for the reading. If the linked scenario is not a basemap scenario, a different heatmap may also be stored. This is essentially a derived attribute, and can be computed using the heatmap for the corresponding basemap scenario.

outdoor_thermal_ simulation_id	Integer	Unique ID for entries in this table
built_ environment_ id_fk	integer	Reference to the Built environment table
heatmap	raster	Raster with the actual heatmap
difference_ derived	raster	Raster with the difference between the heatmap and the heatmap for the base case (if this is not the base case)
time	datetime	Timestamp for heatmap

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