CRC for
Water Sensitive Cities

Determine the microclimatic influence of harvesting solutions and WSUD at the micro-scale

Presented as: FREQUENTLY ASKED QUESTIONS

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Determine the microclimatic influence of harvesting solutions and WSUD at the micro-scale
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Green Cities and Micro-climate – B3.1

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Purpose of this publication

This report meets the key deliverable of Project B3.1: Green Cities and Microclimate of "Determine the microclimatic influence of harvesting solutions and WSUD at the micro-scale". This report builds on a previous interim reports addressing this same deliverable which was completed in December 2012. The interim report provided an outline of the various micro-scale monitoring studies being undertaken in Project B3.1, along with some preliminary findings.

Rather than simply providing an update on the December 2012 interim report, Project B3.1 has decided to meet this deliverable and final report as a document on 'Frequently Asked Questions'. This document is designed to be more user friendly for industry partners. The frequently asked questions are addressed based on the research conducted in Project B3.1, particularly the observational research aimed at determining the microclimatic influence of harvesting solutions and water sensitive urban design at the micro (household) scale. Those questions marked with an asterix * are directly related to the key deliverable.

This deliverable is designed to answer many frequently asked questions relating to urban warmth, heat vulnerability of urban populations, and the role of green infrastructure and water sensitive urban design (WSUD) in addressing adverse climatic conditions of urban areas. While this deliverable addresses the microclimatic influence of harvesting solutions and WSUD at the household scale, it also draws in research from the wider research conducted in Project B3.1 on human health and human thermal comfort, which were the topics of earlier deliverables from December 2013.

As such, this deliverable is a summative piece covering a large proportion of the research conducted to date in Project B3.1 of the CRC for Water Sensitive Cities, and prior to that, the research in Project 3 of the Cities as Water Supply Catchments research program.

Relevant Project B3.1 documents:

- Determine the microclimate influence of harvesting solutions and Water Sensitive Urban Design at the micro-scale (interim report)
- Impacts of harvesting solutions and water sensitive urban design on evapotranspiration
- Assess impacts on human health (heat related stress and mortality)
- Impacts of water sensitive urban design solutions on human thermal comfort.

What is urban heat?

When cities and town are constructed, the natural landscape is dramatically altered. Vegetation and soil are replaced with hard, impervious surfaces and buildings. This leads to the development of unique urban climates that are quite different from those of surrounding natural environments. Urban development can lead to an increase in air pollution, it can modify rainfall patterns, and urban development can lead to higher air temperature.

Higher air temperature in urban areas as a result of urban development is widely reported across cities around the world. Urban areas can be several degrees warmer than their rural surrounds, especially at night. This urban-rural temperature difference is often referred to as the Urban Heat Island. To illustrate this, Figure 1 shows an example where air temperature was around 4 °C warmer in the city centre compared to outside the city. However, air temperature is quite variable across the city, and will change throughout the day.

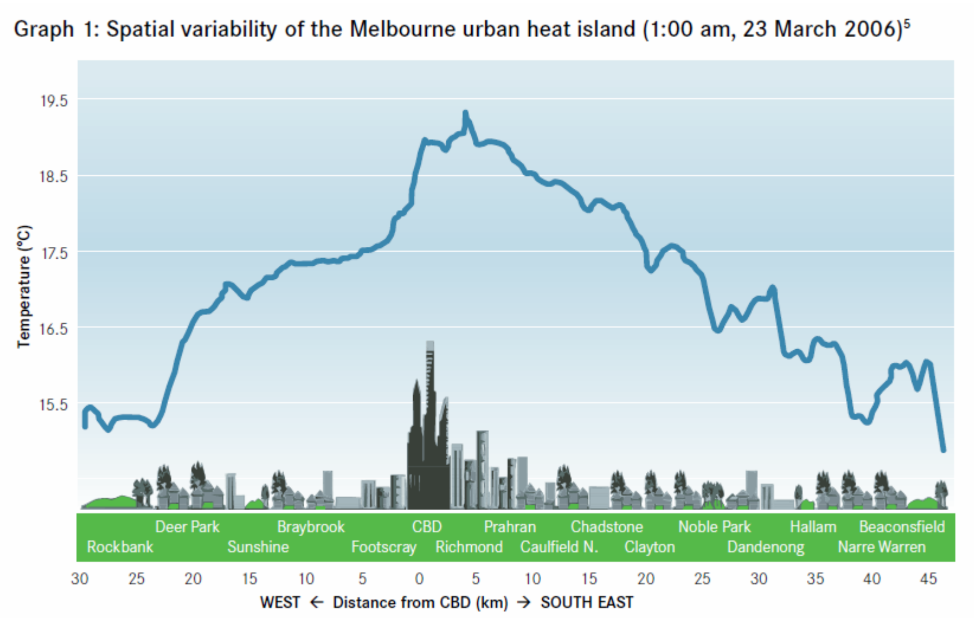

FIGURE 1: Spatial variability of the Melbourne urban heat island at 0100, 23 March 2006. Maximum urban heat island intensity of around 4 C with peak warming in the CBD and high density commercial and residential development to the east of the CBD. Recorded weather at the Melbourne Regional Office at midnight was 19.48C with a westerly wind of 3 knots. The previous day's maximum temperature was 27.0 °C (Coutts et al., 2010)

Why are urban areas warmer?

There are many drivers that support high urban heat and these are outlined in Figure 2. Many urban materials absorb and store lots of energy, so they heat up during the day and then slowly release this energy at night. This means that urban areas cool down slowly, while rural areas cool down quickly and is one main reason why urban areas are so much warmer at night. The complex three-dimensional geometry of urban areas also contributes to urban heat as energy is trapped between buildings and ventilation of heat is reduced. Waste heat from vehicles and buildings also serves to warm urban areas.

These impervious surfaces also prevent rainfall from infiltrating into soils as effectively, and so the water runs off to waterways via the stormwater drainage network. This means less water is available in soils, and when urban vegetation is also removed, means that evapotranspiration rates (the combination of water evaporation and transpiration from vegetation) decline. So, rather than energy (from the sun) being used in evaporating water, the energy contributes to heating the atmosphere instead.

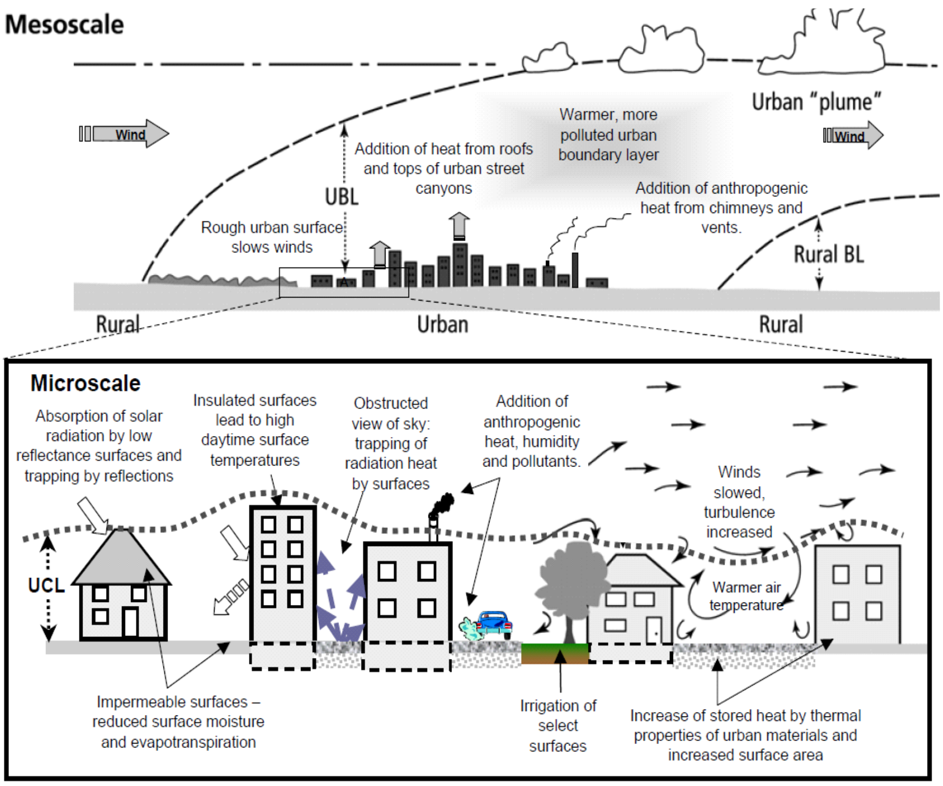

FIGURE 2: Key drivers of urban heat

Why does air temperature vary across the city?

While the peak intensity of the urban heat island considers a comparison between the city centre and the rural outskirts, air temperature can vary quite dramatically across a city, and often over very short distances. Urban development leads to the formation of unique urban climates and because cities vary in their design and layout, the resulting urban climate also varies. Areas that have a high vegetation cover are often cooler, while densely built up areas with lots of concrete can be much hotter. This highlights how the urban climate is fundamentally influenced by the nature of the urban landscape – the design of cities directly influences the urban climate at a range of scales. What this also suggests, is that there is a capacity for our cities and towns to be strategically designed to purposefully modify the urban climate. An example of the spatial variability of urban heat is presented in Figure 3.

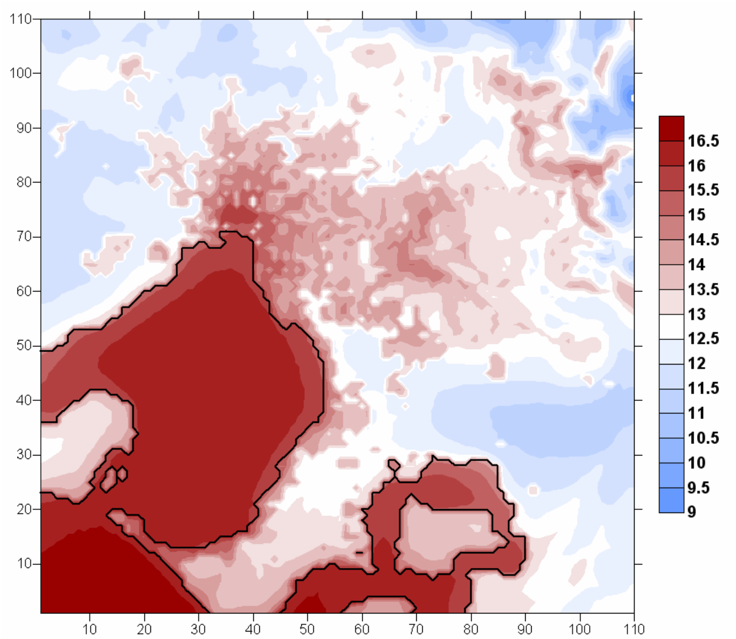

FIGURE 3: Spatial variability in mean screen level temperatures for the Melbourne area at 2 am for January 1997-2004 (Coutts et al., 2008)

How does urban heat vary over time?

Just as air temperature varies across a city, it also varies over time. The peak intensity of the UHI between the urban and rural surrounds is most commonly seen at night, just prior to dawn. However it is important to note that the urban heat island refers specifically to differences in urban-rural air temperature, where urban areas are warmer. At times though, this may not always be the case. If it is very windy or cloudy these differences may not be apparent. Also during the day, the city centre can occasionally be cooler than the rural outskirts due to shading by tall buildings and rapid surface heating in rural areas, while the suburbs may be warmer than both. So, depending on where you are in the city, and what time of the day it is, the way the urban environment influences the local climate around you will change. The local climate will also change depending on the wind direction, the background climate conditions and whether there is a heat wave. In many cities, urban heat becomes more pronounced during warm, sunny, summertime conditions. This is because there is greater surface heating which amplifies the heating effects of the urban environment.

That's all very interesting… but why does it matter?

The urban climate that results from urban development is superimposed upon the background climate. At times, urban heat can have a negative impact upon the urban population and urban infrastructure. In particular during heat waves, the additional heat in urban areas places further pressure on populations and infrastructure including:

- Impacts on human health (mortality and morbidity),
- Poor human thermal comfort and heat stress,

- Compromising urban infrastructure including interruptions to power supplies and public transport services (e.g. buckling of rail lines),
- Increased energy consumption, especially for air conditioning,
- Debilitating work conditions (e.g. outdoor workers, emergency services),
- Loss of productivity,
- Increased potable water consumption,
- Damage to trees and animals.

What is the contribution of urban heat during heat waves?

During a heat wave, air temperature in cities such as Perth, Adelaide and Melbourne, can exceed 40 °C during the day and may remain above 30 °C at night. An additional few degrees of urban heat adds to this, pushing urban populations and infrastructure into even more extreme heat conditions. Unfortunately, it is often during heat waves that urban heating is largest, as more heat is absorbed, trapped and stored in the urban environment, and large amounts of waste heat from air conditioning is produced. Research by (Morris and Simmonds, 2000) found that for all synoptic conditions in Melbourne, the early morning UHI intensity was largest when a high pressure system was situated over the south-east coast of Australia, averaging 3.6 °C. Heat waves in Melbourne occur under these synoptic conditions. The contribution of urban heat to air temperature is largest during heat waves.

However, it is difficult to attribute one value for the contribution of urban heat to air temperature during a heat wave because the exact contribution of urban heat will vary with time and location throughout the city. A comparison of urban and rural air temperature provides a useful idea of the additional heat in the urban environment. Table 1 provides an example of nocturnal urban heat island intensities observed in Melbourne during automobile transects across the city. These examples are at night because this is when the contribution of urban heat is the largest and so often it is the focus of research campaigns.

TABLE 1: Observed urban heat islands in Melbourne and their intensity

Location	Date	Time (EST)	Tmax	UHI intensity	Source
Melbourne	23 Mar 2006	1 am	26.9 °C	4.0 °C	(Coutts et al., 2010)
Melbourne	26 Aug 1992	9 pm	14.1 °C	7.1 °C	(Torok et al., 2001)
Melbourne	25 Feb 2012	12 am	37.1 °C	8.1 °C	(Coutts et al., 2015)
Melbourne	28 Mar 2011	12:30 am	24.3 °C	4-5 °C	Un-published

So can we compare urban and rural air temperature to estimate urban heat?

Comparing urban and rural air temperatures can give an indication of urban warming, but it can be misleading because both urban and rural temperatures vary spatially, and weather station networks are quite sparse. We conducted four transects on 28 March 2011 across Melbourne during both the night (12:30 am) and day (4 pm). At night, a clear UHI can be seen for all transects, but they are all different, and so the UHI intensity will vary depending on which transect you choose. Further, the peak UHI may be irrelevant for a specific suburban location. If urban and rural temperatures were to be compared, then several urban and rural weather stations should be used

The spatial variation in air temperature is described well by the daytime transect. During this transect, the CBD is as cool, if not cooler, than the rural outskirts on this day. The cooler city temperatures may be due to shading from tall buildings, and a southerly afternoon sea breeze. If we compared urban-rural temperatures, the UHI intensity at 4pm on this day is small, or may even represent an urban cool island! However, there is an area of elevated temperatures around 10 km from the CBD in the East/South-East direction. So, whether there is an urban heat island at this time or not, this was an area of high urban heat. During heat events, it is the areas of high urban heat that are of particular concern, irrespective of the presence of an UHI.

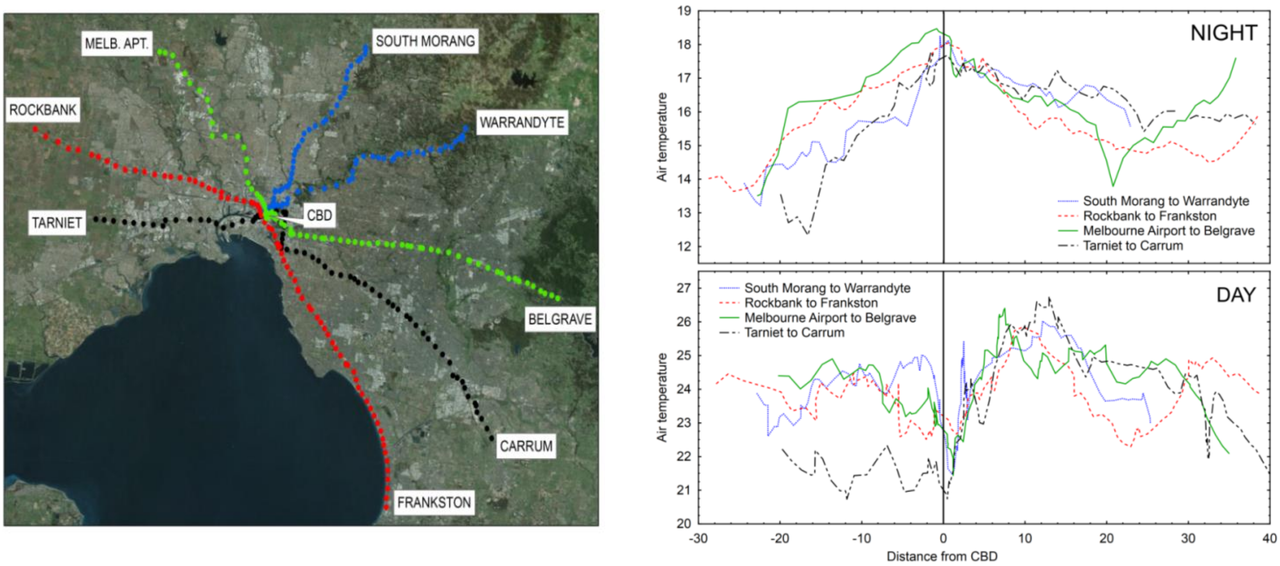

FIGURE 4: Air temperature transects conducted across Melbourne during the night (11:30 pm) and day (4 pm) on 28 March 2011 (un-published)

* So should we consider ‘urban heat’ rather than the ‘urban heat island effect’?

Yes. Urban heat is a better way to describe high urban air temperature given the spatial and temporal variability in air temperature across a city. An urban area may be very hot, and so it is somewhat irrelevant what the air temperature is in a nearby rural area. Comparing urban air temperature to rural air temperature just gives an indication of how much additional heating there is as a result of urban development. If both an urban area and a rural area are very hot (e.g. > 40°C), an urban heat island may not actually exist at the time, but this does not mean that urban heat is not an issue. What is of real importance is the variability in urban heat across the city and what urban landscape features drive this variability. In effect therefore, we have more “environmental control” in urban areas to purposefully modify the urban landscape to reduce temperature below what it otherwise may be, therefore improving human health and human thermal comfort.

This is evidenced by the research we undertook at Mawson Lakes in Adelaide. Under warm summertime conditions, we found that across this mixed use development, air temperature varied by as much as 2.5 °C and varied depending on the location, time of the day and background conditions (e.g. wind direction) (Broadbent, 2015). As such, people will experience different microclimatic conditions depending on where they are, and over the course of a day people will be exposed to a range of microclimate conditions.

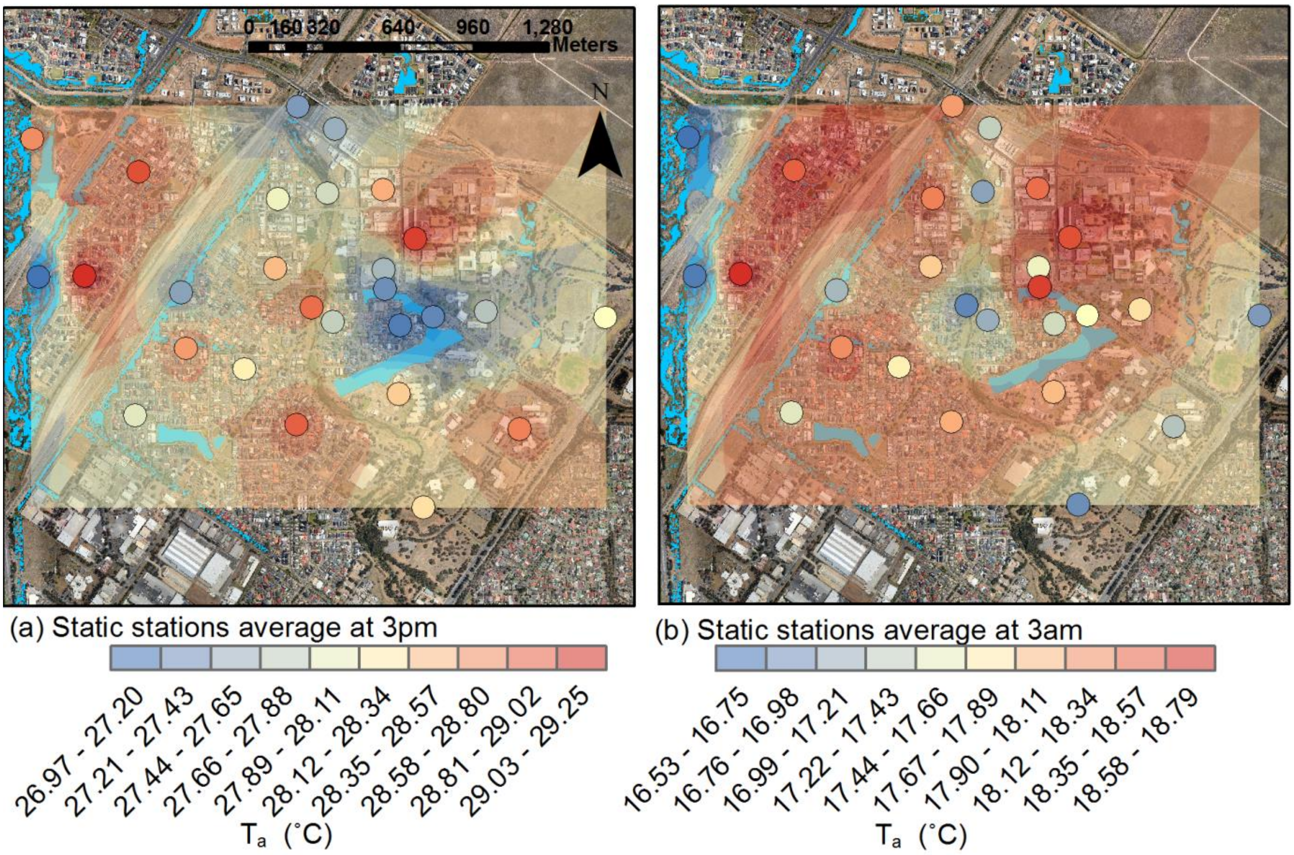

FIGURE 5: Average air temperature for automatic weather stations at (a) 3 pm and (b) 3 am (Broadbent, 2015)

How does urban heat relate to climate change?

Urban heat is driven by urban development, not climate change. Under a changing climate, model projections suggest that average air temperature will increase across much of Australia, and that the frequency, intensity and duration of heat waves will increase in many Australian cities (Alexander and Arblaster, 2009). As such, climate change will place added pressure on our urban society. While urban heat is driven by urban development, climate change and the increased prevalence of heat waves will likely increase the intensity of urban heat. Higher air temperature as a result of climate change will lead to increased air conditioning use, which will produce greater amounts of waste heat, leading to further increases in urban heat and place pressure on populations, infrastructure and services.

Climate change model projections suggest that the number of days with high maximum air temperature (e.g. > 35 °C) will increase, as will the number of days with high overnight minimum temperature. However, these projections use large scale climate models and use a coarse grid of say 200 x 200 km, and so a whole city may be encompassed by just one model grid square. As such, the impacts of urban development on warming are not accounted for, so the frequency of high maximum and minimum temperatures will actually be even greater.

SUMMARY:

- Urban areas experience elevated air temperature at various time throughout the day
- There is a large amount of spatial variability in urban air temperature and is largely driven by changes in urban design
- The contribution of urban heat to air temperature is largest during heat waves
- Urban heat can be addressed through purposeful modification of the urban landscape

What are the health impacts of heat waves?

Heat waves take more lives in Australia each year than any other natural disaster. In Victoria in 2009, a heat wave hit where air temperature exceeded 43 °C for three consecutive days from 28-30 January. Some 374 excess deaths were attributed to the heat wave and there were 2820 excess emergency department presentations across Victoria (DHS, 2009). There was an 8.4-fold increase in emergency department presentations for heat-related illnesses (heat stroke, heat syncope and dehydration). At the Alfred Hospital in Melbourne, there was a significant increase in total hospital admissions, emergency department presentations and general medical admissions (Lindstrom et al., 2013).

Heat stress can occur even when the human body core temperature rises slightly above the normal body core temperature of 37°C. How the body responds to heat varies with physiological parameters (age, gender, weight, height, etc.) the amount of clothing, the level of activity (e.g. resting, walking, working outdoors) and a range of environmental parameters, not just air temperature (Figure 6). Environmental parameters also include ventilation (wind speed), humidity and mean radiant temperature (total radiation loading on the body e.g. from the sun and warm terrestrial surfaces). The combination of all these factors determines a person’s level of heat stress during a heat wave and is often described as the human thermal comfort. When a person experiences an extended period of heat stress, this is when a heat-related illness tends to occur.

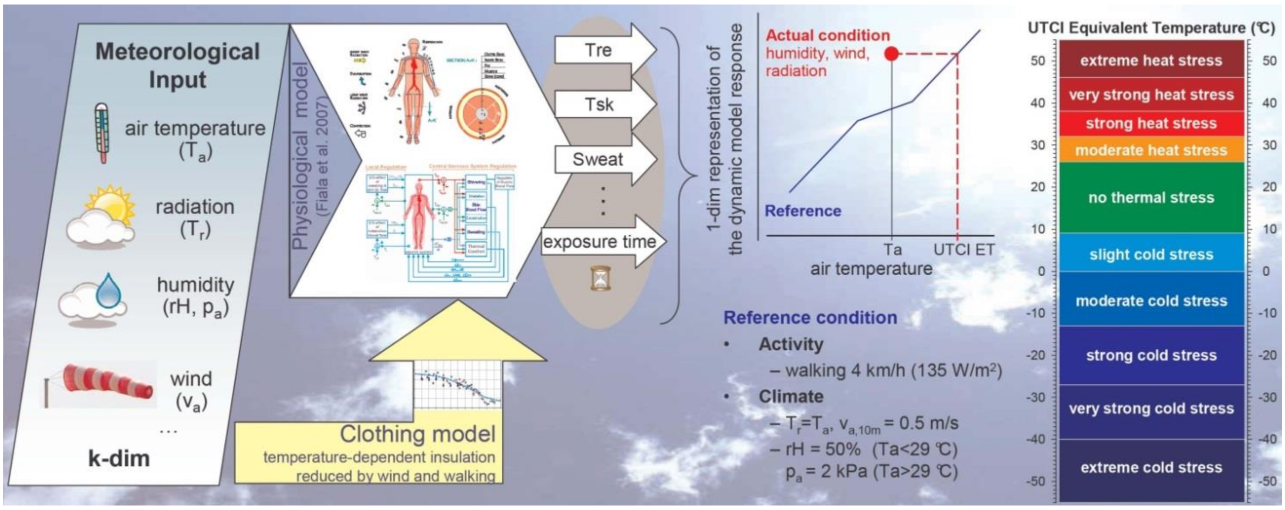

FIGURE 6: Concept of Universal Thermal Climate Index derived as equivalent temperature (Bröde et al., 2012)

What is the contribution of urban heat to these health impacts?

Urban heat can add several degrees to the background air temperature during a heat event depending on the time of day and the location. Increases in air temperature from urban development vary depending on the design of the urban landscape. Those living in urban areas are exposed to higher air temperature throughout the day because of urban heat. According to (McMichael et al., 2006) "while most heat wave deaths occur in people with pre-existing cardio vascular diseases (heart attack and stroke) or chronic respiratory diseases, people living in urban environments are at a heightened risk due to the Urban Heat Island." Further, (Johnson and Wilson, 2009) note that for heat related deaths during a heat wave in Philadelphia that "…heat related mortality was highest amongst the urban poor and the deaths were concentrated in areas with higher UHI intensity levels. "

Higher air temperature throughout the day will place stress on urban populations and infrastructure, but the generally larger contribution of urban heat at night also has a major impact. High nocturnal air temperature limits overnight recovery from daily heat stress. (Clarke and Bach, 1971) state "… it is not necessarily the maximum temperatures, but the lack of relief when the minimum temperatures remain high which causes a rise in mortality rates during periods of extreme heat." Ultimately though, reductions in air temperature and heat stress at any time during the day will have a benefit for urban populations. Table 2 identifies the cities where urban heat has a significant impact on heat-health outcomes and when.

TABLE 2: Relationship between heat-related health outcomes and presence of an UHI in Australian capital cities (Loughnan et al., 2013 and the CRC for WSC)

City	Urban heat (day/night)	Significant predictor of increased risk
Brisbane	Night	Yes ($R2 = 0.38$, $p = <0.001$)
Canberra	-	No
Hobart	-	No
Adelaide	Day & night	Yes ($R2 = 0.34$, $p = <0.001$)
Sydney	Night	Yes ($R2 = 0.19$, $p = <0.002$)
Melbourne	Day & night	Yes ($R2 = 0.21$, $p = <0.001$)
Perth	Night	Yes ($R2 = 0.27$, $p = <0.003$)
Darwin *	NA*	NA*

How hot does it need to get before these health impacts begin to emerge?

Loughnan et al. (2013) used a consistent national approach to determine threshold air temperature at which increases in mortality and morbidity are expected. The thresholds relate to either maximum, minimum and/or mean daily temperatures (the average of today's maximum temperature and tonight's minimum temperature) and apply to the population as a whole.

TABLE 3: Recommended temperature thresholds for each capital city based on city-specific mortality measures (Loughnan et al., 2013)

City	Threshold	Frequency of occurrence over 11-year reference period	% increase in morbidity	Health measure used to determine threshold
Adelaide	Tmax 42 °C	21 days	2-8	Daily mortality
Brisbane	Tmean 31 °C	6 days	15	Daily mortality
Canberra	Tmax 33 °C	179 days	5	2nd daily mortality
Darwin	Tmin 29 °C	19 days	8	Weekly mortality
Hobart	Tmax 35°C	13 days	11	2nd daily mortality
Melbourne	Tmean 28 °C	112 days	3-13	Daily mortality
Perth	Tmax 44 °C	21 days	30	Daily mortality
Sydney	Tmax 38 °C	3 days	2-18	Daily mortality

TABLE 4: Recommended temperature thresholds for each capital city based on city-specific morbidity measures (Loughnan et al., 2013)

City	Threshold	Frequency of occurrence over 11-year reference period	% increase in morbidity	Health measure used to determine threshold
Adelaide	Tmean 39 °C Tmin 31 °C	1 day 4 days	24 5 (15 Triage 1)	ED presentations
Brisbane	Tmax 36 °C	55 days	2.5-12	Ambulance call outs
Canberra	Tmax 37 °C	33 days	5-10	Ambulance call outs
Darwin	Tmean 31 °C	19 days	7	Heat-related ED presentations
Hobart	Tmin 18°C	28 days	5-20	Ambulance call outs
Melbourne	Tmax 44 °C Tmean 34 °C	5 days 6 days	3 3	Ambulance call outs Ambulance call outs
Perth	Tmax 43 °C	3 days	14	Ambulance call outs
Sydney	Tmax 41 °C	3 days	5-38	EHA

These data can be used as a target for heat mitigation approaches to protect the urban population. For example in Perth, we need to aim to keep maximum temperatures (Tmax) below 44 °C or there is likely to be a significant increase in mortality rates. For the elderly (>65 years) who are more vulnerable to the effects of extreme heat, the specific threshold temperatures are different. (Nicholls et al., 2008) found that in Melbourne, when minimum overnight air temperature exceeds 24 °C there is a 19-21% increase in mortality and when the mean daily air temperature exceeds 30 °C there is a 15-17% increase in mortality.

Why are the elderly so vulnerable to heat waves and who else is vulnerable?

All members of society are potentially at risk from excessive heat, but it is the very young and very old age groups that are most at risk. (Loughnan et al., 2013) provide a detailed review of heat-health vulnerability. A key reason for vulnerability of older folk is that they have a reduced ability to thermo-regulate and they also carry an increased burden of disease (e.g. cardiovascular, respiratory, renal and cerebrovascular disease) that are prominent causes of death during extreme heat events. There is also considerable evidence that people who are poorer, are disabled, or who speak languages other than English, are at greater risk during extreme heat events (Loughnan et al., 2013)

It's ok; we have heat wave plans in place to deal with heat waves.

Heat wave plans are an important component of managing heat waves, but they are a response to high air temperature and do not deal with actually reducing the air temperature through urban design. Heat-health outcomes are dependent on a person's exposure to extreme heat, their vulnerability and their adaptive capacity (Tapper et al., 2014) (Figure 7). Heat wave plans tend to focus on planning and prevention in the area of reducing vulnerability and building adaptive capacity, and responding to heat related impacts and supporting recovery. Measures include identifying vulnerable individuals, disseminating information, coordinating service providers and working with the media.

Heat wave plans essentially manage the impact of the heat events. However, heat wave plans do not target the area of reducing the overarching exposure of heat which is a combination of the regional climate (e.g. the heat wave) and the superimposed urban climate. As such, in years to come as urban development (that does not consider urban climate) continues and projected climatic changes eventuate, populations will need to cope with ever increasing levels of heat exposure. As such, heat wave plans, urban planning, and urban design must target reducing exposure.

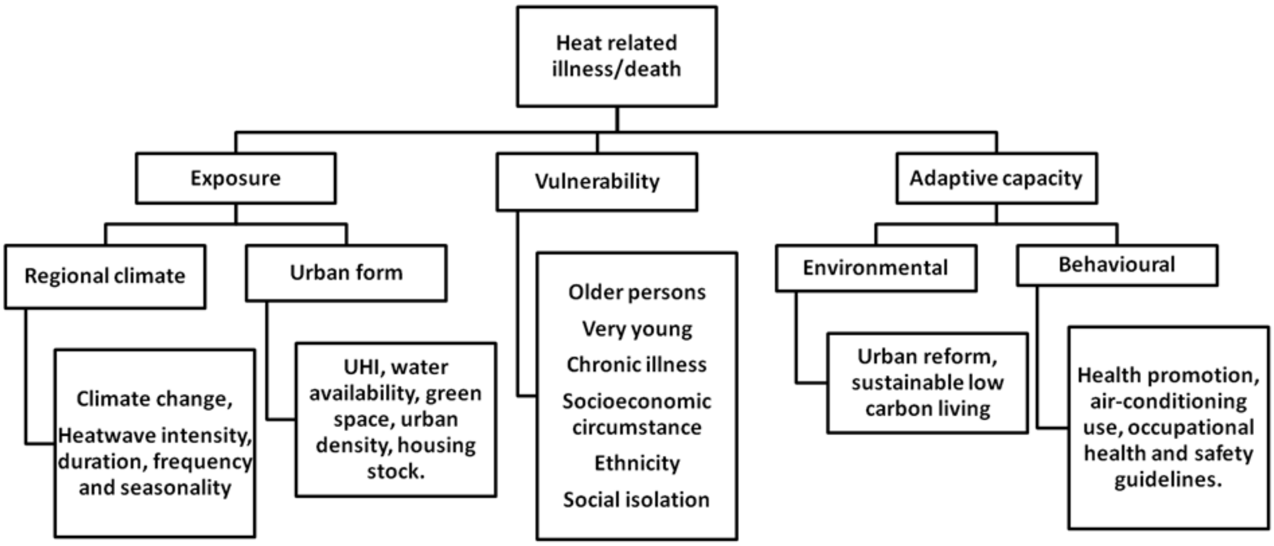

FIGURE 7: Schematic diagram showing the relationship of exposure, vulnerability and adaptive capacity to heat-related human health outcomes (Tapper et al., 2014)

SUMMARY

- Urban heat contributes to high air temperatures during heat waves
- Areas with high urban heat place additional pressure and strain on vulnerable populations
- There are threshold air temperatures at which health related illnesses and deaths increase substantially
- Urban heat mitigation is needed to reduce exposure to high urban temperatures

How do we reduce urban heat?

The design of urban environments has a direct influence on the development of urban climates. There are a range of approaches that can be used to mitigate urban heat (Coutts et al., 2010).

TABLE 5 Approaches to reducing urban heat (Coutts et al., 2010)

No.	Measure	Why it works
1	Increase vegetation	Vegetation is a natural cooling mechanism as it encourages evapotranspiration, and energy is dissipated more through latent heating rather than sensible heating. It can also be a sink for CO_2. The type of vegetation can also be important.
2	Water-sensitive urban design	Retaining water in the urban landscape enhances evaporation. Stormwater capture and re-use for irrigation supplies water to the landscape. Higher vegetation cover, green roofs and open space aids this. Other measures include rainwater tanks, buffer strips, infiltration trenches, porous pavements and rain-gardens.
3	Increased albedo	Highly reflective materials and light coloured surfaces such as elastomeric, polyurethane or acrylic white thick paints reflect greater amounts of solar radiation, reducing heat storage and net radiation. Measures that limit heat transfer into buildings can reduce the need for summertime indoor cooling.
4	High thermal emittance surfaces	Roofing material such as tiles can be coated in reflective material containing pigments that reflect in the near infrared. This allows traditional rooftop colours to be retained. Combined with high albedo surfaces, heat storage in buildings, pavements and roads can be significantly reduced.
5	Outdoor landscaping	Vegetation placed on the east, west and north (in Australia) sides of dwellings can block solar radiation on buildings and reduce heat storage. Deciduous varieties drop leaves in winter so sunshine can still reach dwellings. Can also be a sink for CO_2.
6	Street design	E–W oriented street floors are exposed to sunlight all day, while on N–S oriented streets buildings shade the street from radiant heating. However, this limits favourable wintertime sunshine. NW–SE and NE–SW oriented streets are a good compromise. Widening street widths as building heights increase allows ventilation to continue. H:W should be controlled appropriately.
7	Parkland and open space	Vegetated open space can provide a cooling impact including regions downwind. Anticipated busy areas should have parklands situated upwind of a centre in the dominant wind direction. The region influenced by a park is a function of its size and design.
8	Green roofs	Green roofs can reduce heat transfer into buildings and encourage evapotranspiration. Climbing plants have the same effect on walls. Green roofs can retain water in urban areas and decrease stormwater intensities and nutrient loads. Can also be a sink for CO_2.
9	Energy efficiency	Using products that have excellent energy efficiency ratings reduce energy consumption and hence greenhouse gas emissions. Waste heat production is also often reduced in these products.
10	Evaporative air coolers	Some air conditioners release waste heat outside of dwellings, increasing outdoor ambient temperatures and increasing cooling requirements. Passive coolers do not raise ambient temperatures and consume less energy. Increased water consumption is a drawback.
11	Building design	Well-insulated roofs and walls, double-glazed windows and sufficient ventilation, for example, can reduce heating and cooling needs. Specifics of building design are determined by the climate of the city, for example, Tropical, Desert, Temperate.
12	Mass transport	Shifting commuter travel to public transport reduces vehicle usage which is the major urban source of CO_2 and a large contributor of anthropogenic heating.

Which is the best approach to reduce urban heat?

Each approach has an important place in mitigating urban heat, and to achieve maximum air temperature reductions during extreme heat events, a mix of approaches is recommended. However, research has shown that vegetation, especially trees, has a particularly strong benefit and is the best approach. Not only does vegetation help mitigate urban heat, but trees also provide shade and therefore limit heat stress by reducing solar radiation loading on the body. Vegetation also delivers multiple benefits that some other approaches do not. These include reduced stormwater flows and improved stormwater quality benefits, improved amenity, benefits for air quality and they support CO2 uptake. Trees can also shade buildings and so reduce summer energy demand for cooling.

Another approach that is particularly beneficial is water sensitive urban design (WSUD). WSUD reduces air temperature by retaining water in the urban landscape and increasing soil moisture. This promotes evapotranspiration and leads to a cooling effect, much like an evaporative cooler. The other critical role of WSUD is that it increases water availability for vegetation to strengthen the cooling effect of vegetation and keep it healthy. For trees and vegetation to provide maximum cooling capacity, it must have sufficient access to water to support transpiration and maintain a healthy canopy to provide shade. WSUD also supports a range of multiple benefits. Integrating WSUD and vegetation, especially trees, should be a key component of any urban heat mitigation strategy.

How much cooling can be achieved from WSUD and urban greening?

Before addressing this question, it is important to consider the scale at which this question is being considered: e.g. at the scale of the household, street, neighbourhood or city. Implementation of WSUD and greening generally occurs at the household and street scale (the micro-scale) through planting of street trees, construction of WSUD elements like biofiltration systems, and creation of open space. These micro-scale implementations will influence the micro-climate. When WSUD features and urban greening is widespread across the neighbourhood, it will have an influence on the local-climate. Extensive irrigation across a neighbourhood will also influence the local climate. This is presented conceptually in Figure 8 which shows the widespread implementation of WSUD and urban greening at the micro-scale, and the anticipated benefits at the local-scale (Coutts et al., 2013). When several neighbourhoods begin to support cooling through these and other mitigation approaches, this is when the city-scale urban heat island will be reduced.

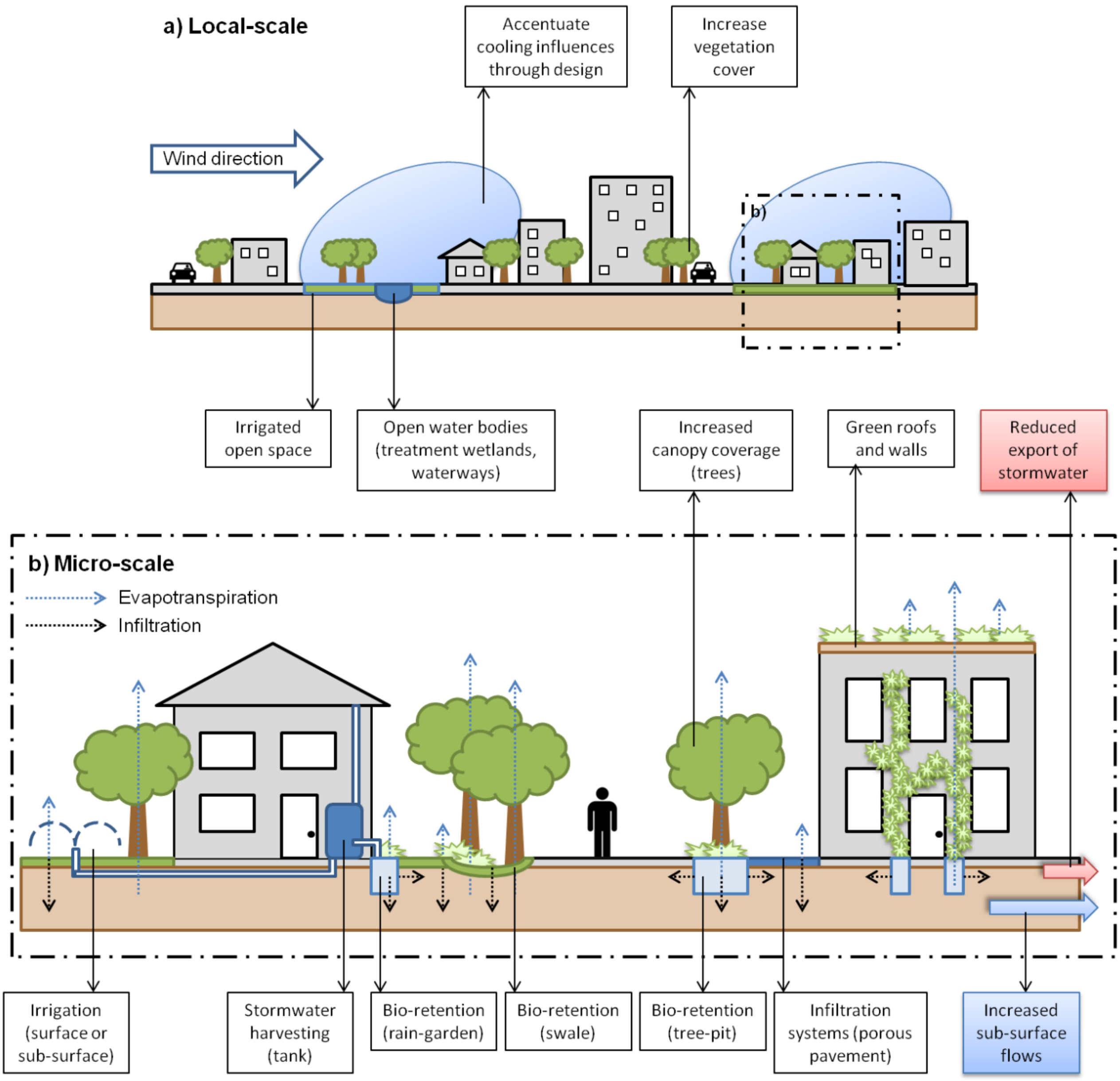

FIGURE 8: Schematic representation of widespread implementation of stormwater harvesting and Water Sensitive Urban Design elements at the micro-scale in the restoration of a more natural water balance, along with increased vegetation cover. This enhances urban evapotranspiration and shading resulting in local-scale cooling effects that can improve human thermal comfort.

Just as urban heat varies both spatially and temporally, the amount of cooling provided by WSUD and urban greening at a range of scales will vary spatial and temporally. The focus however should be on the cooling during heat waves because this is when it is most needed. Cooling will depend upon:

- The type and size of feature (e.g. trees, biofiltration systems, green walls etc.),
- Water availability,
- The design and arrangement of the WSUD and urban greening features,
- The background climate (e.g. wind direction, prevailing weather conditions, regional climate),
- The surrounding built environment (e.g. density and arrangement of buildings).

* How much cooling is provided by a single WSUD or greening feature (i.e. at the micro- or household-scale)?

The cooling effect of an individual WSUD or greening feature is highly localised. We explored the cooling effect of a single isolated tree in Melbourne in February-March 2014. We selected an isolated tree and instrumented a cross sectional array of 35 temperature sensors through the centre of the tree canopy. On very hot days (e.g. 8 February and 9 March) at 4pm, the temperature below the tree canopy was 0.6-1.2 °C cooler than immediately upwind of the tree (Figure 9) as a result of shading and subsiding cool air from within the canopy. There was also very high water use from the tree that would contribute to the overall local-scale cooling. At night, air temperature above the canopy was also cooler, but below the canopy, air temperature was actually slightly warmer by around 0.2 °C.

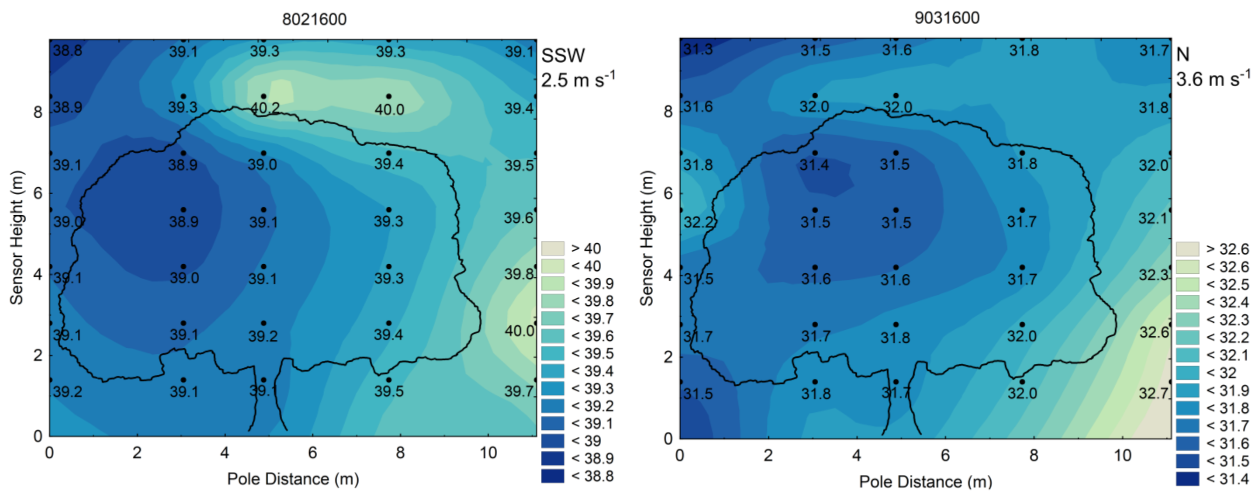

FIGURE 9: Tree cooling at 4pm on 8 February and 9 March in 2014.

When considering human thermal comfort on the human body, a single tree can dramatically reduce the level of heat stress. We compared human thermal comfort levels outside and below tree canopies in the CBD of Melbourne in Bourke St. We used a thermal comfort index call the Universal Thermal Climate Index (UTCI) to describe heat stress during a heat wave on 24-25 February 2012. We found that shading dramatically reduced the mean radiant temperature and the UTCI was reduced from a level of ‘very strong’ heat stress to ‘strong’ heat stress (Coutts et al., 2015) (Figure 10). Shading is the key mechanism for reducing heat stress during the day under warm, sunny conditions. This study also showed that mean daytime air temperature under warm, sunny conditions could be up to 1 °C cooler under the tree canopy compared to out in the open.

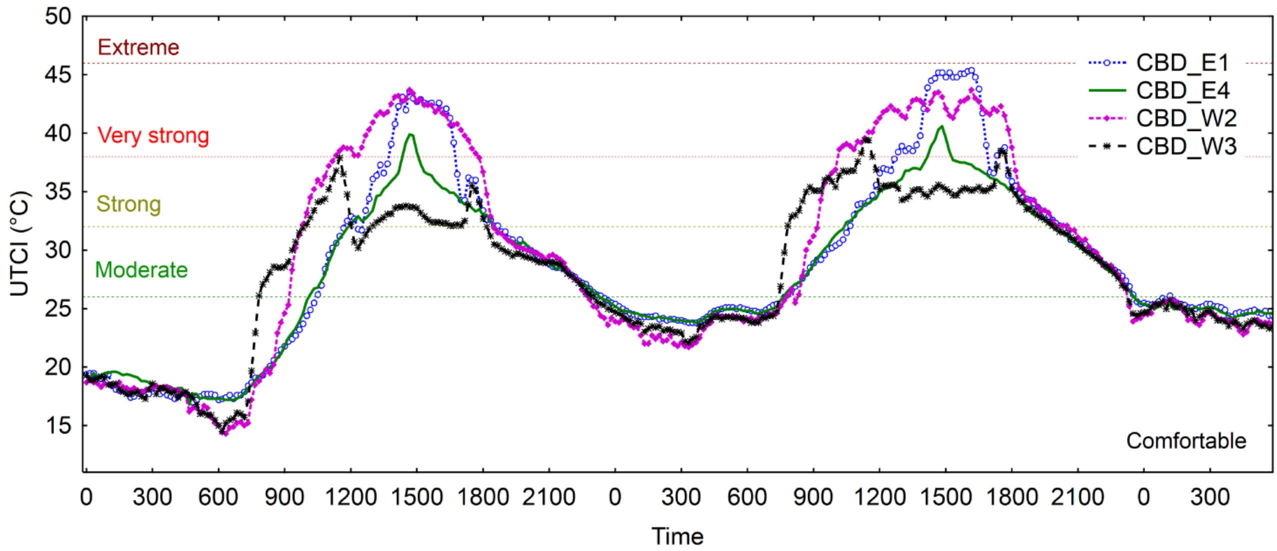

FIGURE 10: Universal Thermal Climate Index (UTCI) and human thermal comfort (HTC) at selected stations over the 24–25 February 2012 for selected stations in Melbourne’s CBD (Coutts et al., 2015)

* How far downwind does the cooling effect extend?

The isolated tree research demonstrated that cooling is highly localised, with cooling below and immediately downwind of the tree canopy. Research on the downwind cooling effect of urban parks suggests that downwind cooling extends to about one park width (Spronken-Smith and Oke, 1999). This ‘rule of thumb’ is similar to that observed for this isolated tree. This rule of thumb can be broadly applied to any WSUD and greening feature: the cooling effect will extend up to a distance equal to the width of the feature.

The downwind cooling effect of water bodies can be seen from the observations undertaken at Mawson Lakes in Adelaide. We undertook bicycle transects throughout the neighbourhood to observe the variability in air temperature. Air temperature is presented in Figure 11 at 2 pm for two consecutive days (15 and 16 February 2011) when wind direction from the North-East and South-West respectively. Looking at the lakes, the downwind side of the lake is cooler and varies with wind direction.

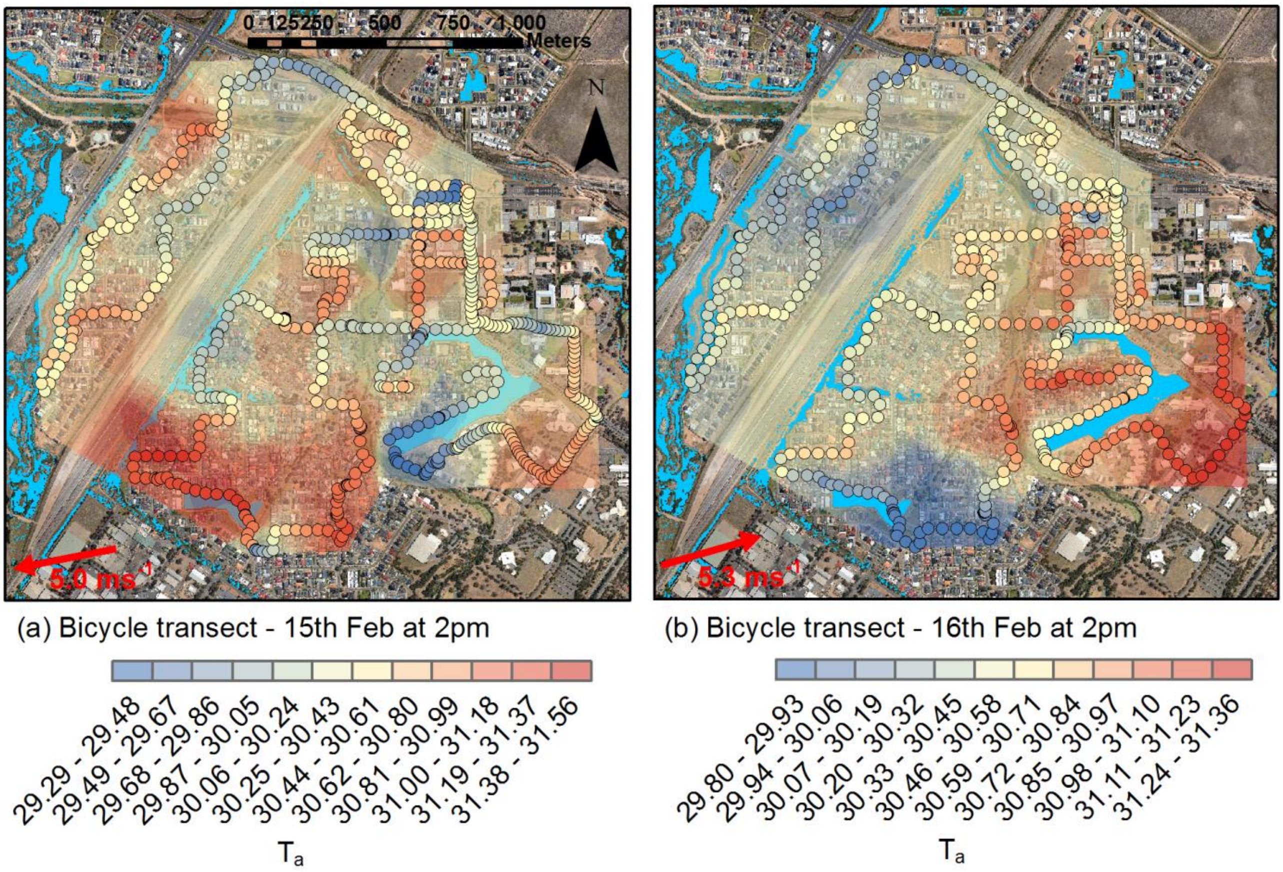

FIGURE 11: Two case study examples of daytime bicycle transects conducted throughout Mawson Lakes: (a) 15th February at 2pm and (b) 16th of February at 2pm (Broadbent, 2015)

* How much cooling is provided when WSUD or greening features are implemented in a street?

Cooling from individual WSUD and greening elements is clear, though when considering a larger area, other factors come into play, such as building heights and street geometry. We undertook a study that compared the micro-climate in two residential streets in East Melbourne over 2011-2013. The two streets were very similar in terms of street width and adjacent building heights, but one street was open (OPN) with very little tree canopy cover (12%) and the other (TRD) had a good tree canopy cover (45%). During the day during hot conditions on 24-25 February, air temperature in the street with trees was 0.2-0.6 °C cooler than the street without, and up to 0.9 ° during the morning as the trees delayed surface heating. Moreover, heat stress was lower in the street with trees.

The amount of cooling depends in part on the surrounding built environment. We also monitored air temperature in Bourke St in the Melbourne CBD at the same time. Bourke St had a tree canopy cover of 31% but also had tall buildings. We found that the influence of the trees on the microclimate was overwhelmed by the influence of the tall buildings. The buildings provided shade during the day and so lowered heat stress, but at night, the tall buildings trapped heat and radiation so air temperature in Bourke St was up to 4.8 °C warmer than the street with trees during these hot conditions!

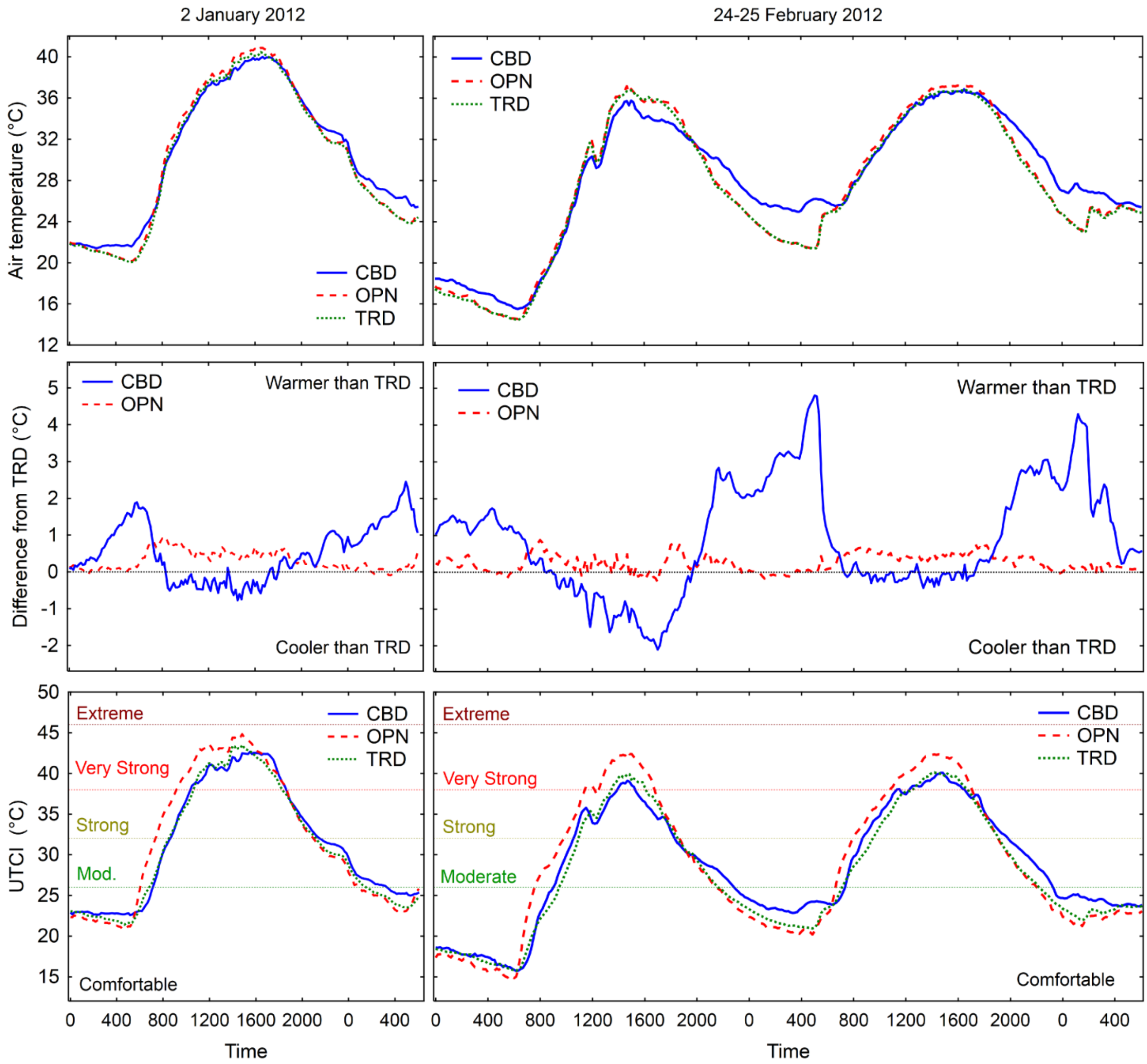

FIGURE 12: Mean air temperature for each street during heat events on 2 January 2012 and 24–25 February 2012, differences in air temperature for CBD and OPN in comparison with TRD (Difference from TRD), and UTCI for each site and the corresponding grades of heat stress.

Considering human thermal comfort, we explored the impact of increasing tree canopy cover on mean radiant temperature which is the dominant driver of human thermal comfort during warm summer conditions and so directly affects heat stress. Using a micro-scale model called SOLWEIG, we modelled the mean radiant temperature of areas within Mawson Lakes. After validating the model, we compared existing conditions with those following a widespread increase in tree canopy cover. The introduction of trees resulted in large reductions in mean radiant temperature across the whole area (Thom et al., 2014). Again, trees have the dual function of providing both shade AND transpiration, as well as modifying thermal and radiative effects in the urban environment. As well as providing shading and reducing mean radiant temperature as shown here, they can also act as ‘mini’ oases.

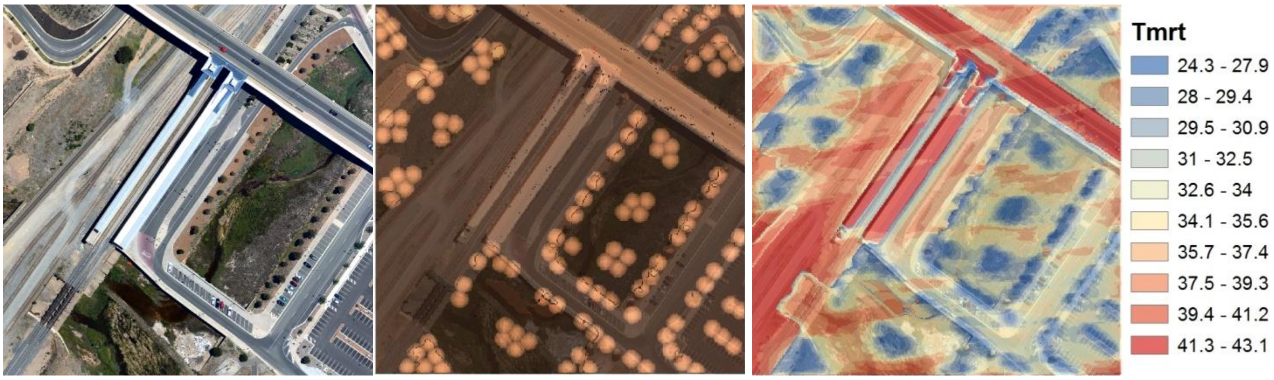

FIGURE 13: Reduction in mean radiant temperature from an increase in tree canopy cover at the micro-scale (Thom et al. 2015)

* How much cooling is provided by an urban park?

Greenspace can help to cool urban environments, and urban parks of various sizes are often observed to be cooler than the surrounding urban landscape. Again, the effects of these green spaces tend to be highly localised, and their influence varies with their size, design (e.g. amount and distribution of trees), irrigation regimes and the local meteorology. Their influence also varies with the nature of the surrounding urban landscape. To explore this further, 11 microclimate stations were established in a small park in a built up area in Carlton, Melbourne, to observe the influence of the park on air temperature and human thermal comfort, in the context of its surrounding urban environment. During an extreme heat event in January 2014, air temperatures were up to 1.2 °C cooler in and around the park than the adjacent streets (Figure 14). There appeared to be some downwind cooling to the southeast of the park under the northerly wind direction at the time.

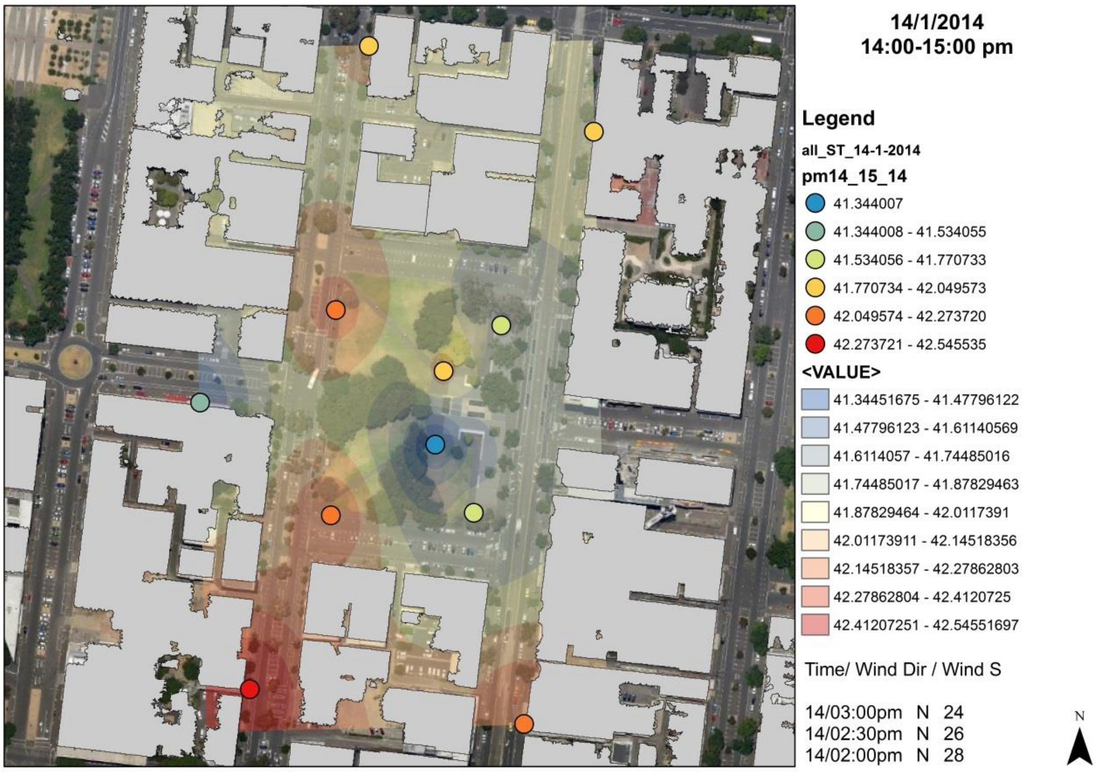

FIGURE 14: Air temperature in and surrounding a park in Carlton, Melbourne on 14 January 2014 from 2pm to 3pm (Motazedian et al. 2015)

How much cooling is provided from widespread implementation across a neighbourhood?

Because cooling effects from WSUD and urban greening are highly localised, they need to be implemented widely across a neighbourhood to drive local-scale cooling. We undertook a study that explored the influence of widespread irrigation on urban cooling. The town of Dubbo, NSW is often well irrigated, and offered an opportunity to explore the effect of widespread irrigation on Dubbo's land surface temperature compared with the surrounding countryside (Figure 15). Using satellite remote sensing, we observed that during dry conditions, the land surface temperature of the dry rural surrounds was 3-5 °C warmer than much of Dubbo where extensive irrigation occurred.

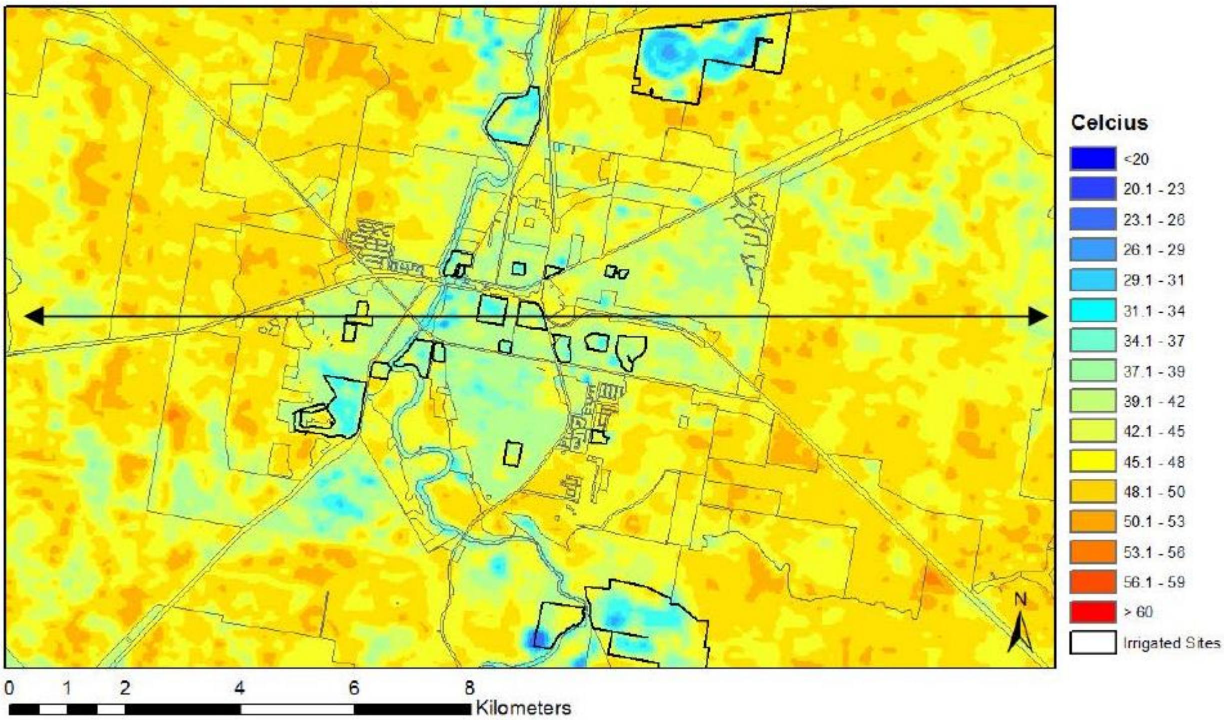

FIGURE 15: Landsat TM imagery data for Dubbo, Western New South Wales on 13 January, 2005 showing the land surface temperature (LST)

The pattern in land surface temperature in Dubbo supports the idea of converting the city into an oasis. By supporting the notion of 'cities as a water supply catchments' where stormwater is harvested and reused in the urban landscape for irrigation, we can theoretically create 'cities as oases'. This concept was captured well in a study by Spronken-Smith et al. (2000) who investigated evapotranspiration rates across an irrigated park in Sacramento, California. The idea is presented in Figure 16 below, and Spronken-Smith et al. (2000) observed that the wet park evaporated as much as three times more water than from the surrounding residential neighbourhood. Oke (1987) points out these oasis effect advection situations can occur whenever there is a cool, moist surface that is dominated by larger-scale warmer and drier surroundings – including an isolated tree in a street. Widespread implementation of household and street scale WSUD and greening features, and making water available, will support increases in neighbourhood evapotranspiration. Each individual WSUD and urban greening element (that is well watered) can potentially support 'mini' oasis effects, and when combined, reduced air temperature at the neighbourhood scale.

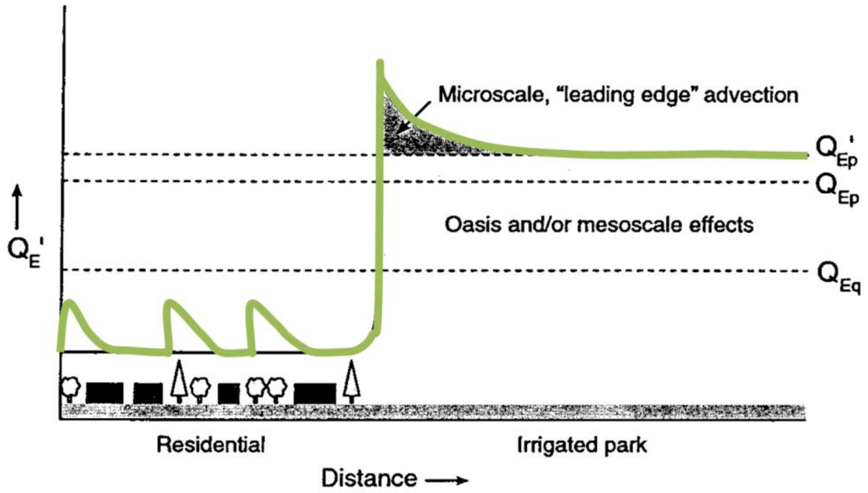

FIGURE 16: Hypothesized variation of the latent heat flux with distance of fetch as air traverses from a residential suburb across an irrigated urban park (after Spronken-Smith et al., 2000). Irrigation at the micro-scale of vegetation may create micro-scale 'leading edge' and 'oasis effects'.QEq is the equilibrium evaporation (Q-QG), QEp is the potential evaporation and QE'p is 'local' potential evaporation.*

More information related to this question is provided in a complimentary report "Determine the micro-climatic impacts of harvesting solutions and WSUD at the neighbourhood to catchment scale using both modelling approach and data gathered from field measurements."

SUMMARY:

- There are a range of approaches for reducing urban air temperature and improving human thermal comfort
- At the micro-scale, trees are particularly effective at reducing air temperatures and improving human thermal comfort, particularly during the day.
- Downwind cooling effects are highly localised, which means WSUD and urban greening must be implemented is a regular and distributed manner.

I only have a limited budget to implement WSUD and greening, what should I do?

Prioritise. The aim is to get the largest amount of cooling and reduction in heat stress for the investment. We co-developed a framework for prioritising the investment of green infrastructure (Norton et al., 2015) that can be applied to WSUD and urban greening to maximise the thermal benefits. The framework identifies areas for prioritisation based on areas that have high exposure (high urban heat or 'hotspots'), areas with a high population vulnerability, and areas where people frequently visit, thereby increasing their behavioural exposure (such as public spaces, health centres, train stations). Implementing WSUD and greening in locations where these intersect will deliver the greatest benefit.

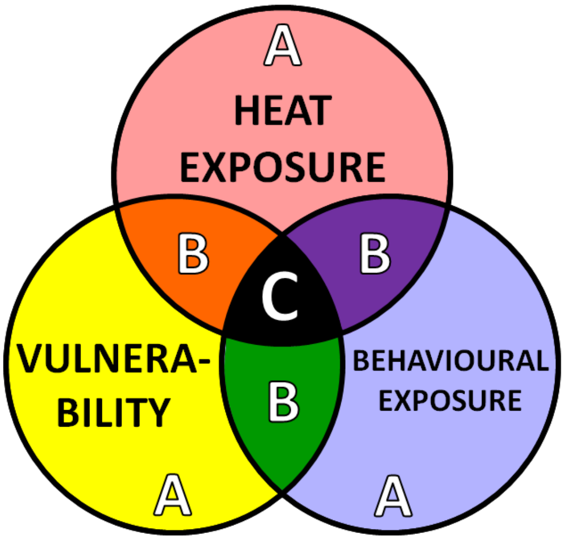

FIGURE 17: Factors required to identify neighbourhoods of high (C), medium (B) and moderate (A) priority for UGI implementation for surface temperature heat mitigation. The key factors are high daytime surface temperatures (Heat exposure) intersecting with areas with more vulnerable sections of society (Vulnerability) and identifying the zones of high activity (Behavioural exposure) within this area (Norton et al., 2015)*.*

How do I determine areas of high heat exposure or 'hotspots'?

The quickest and cheapest approach to identify hotpots is to use satellite thermal remote sensing. There are a range of options available including Landsat 8 and MODIS which provide an excellent spatial coverage of land surface temperature. A key assumption in the use of thermal remote sensing is that the output of land surface temperature follows the same pattern as air temperature. This is broadly true, though under some circumstances the assumption falls down (e.g. due to advection and turbulent mixing).

Landsat 8 provides a 30 m resolution image of land surface temperature that can be used to identify hotspots across the landscape. The overpass time of Landsat 8 is during mid-morning and so it does not capture at the time of the most intense surface heating. We compared a Landsat 7 thermal image captured mid-morning on 25 February 2012 with a high resolution airborne thermal map captured in the early afternoon at the peak time of land surface temperature heating for the City of Port Phillip. After resampling the high resolution thermal map to the same resolution as the Landsat 7 map, we found that 'hotspots' were generally located in the same area (Coutts et al., 2014). This means that the Landsat satellite thermal infrared series can be confidently used to identify hotspots.

(Note: Landsat 7 contains missing data, however Landsat 8 was launched in February 2013 and provides complete data coverage).

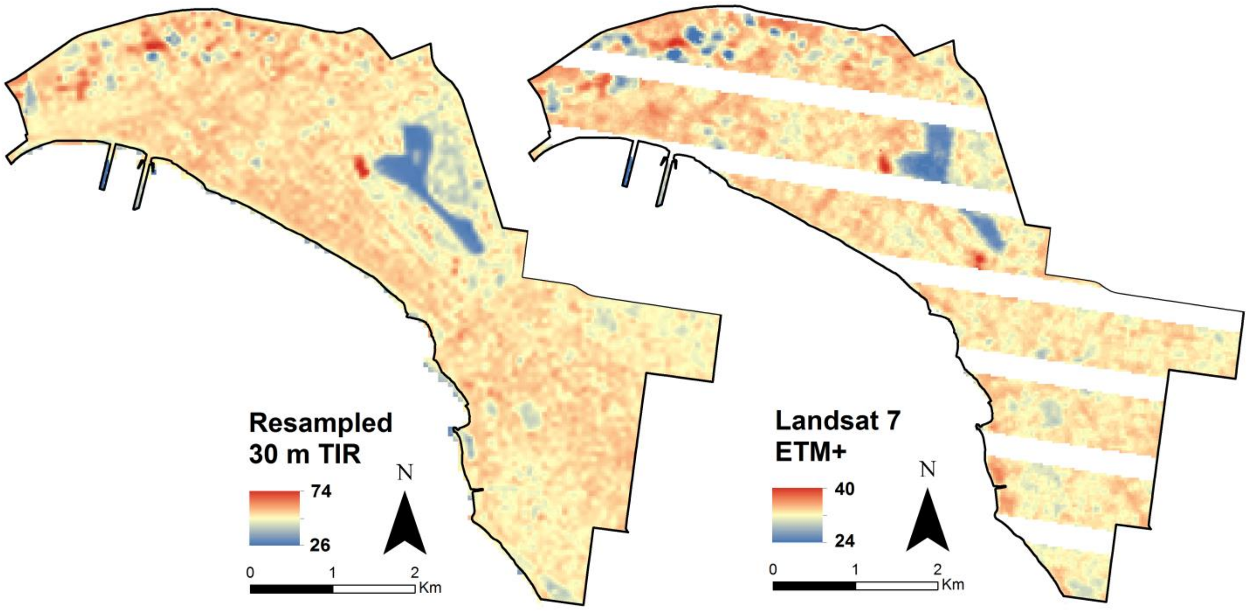

FIGURE 18: Comparison of patterns in land surface temperature throughout the City of Port Phillip on 25 February 2012 between the daytime (13:00) high resolution thermal infrared (TIR) remote sensing data (left) (aggregated to 60 m and resampled to 30 m using cubic convolution); and b) the daytime (11:00) Landsat 7 ETM+ thermal image (right) (Coutts et al., 2015).

How do I determine areas of high population vulnerability?

Loughnan et al. (2013) identified a number of risk factors that contribute to a location's vulnerability. These include:

- High risk age groups (0-4, > 65)
- Low socio-economic status
- Poor access to emergency services
- A high proportion of:
    - Disability
    - Ethnicity (groups whose first language is other than English)
    - Persons living alone (and > 65)
    - Multi-dwelling structures
    - Population density
    - Non-green areas (high proportion of imperviousness)

Developing a vulnerability index that includes all of the risk factors is challenging. In the case study, we chose a selection of risk factors to include in the priority mapping. It is expected that local government staff and residents will have a good knowledge of likely risk factors for their municipalities, and can select all risk factors, or those deemed most critical. Information can be drawn from the Australian Bureau of Statistics. Loughnan et al. (2013) also identified areas of high urban heat as a risk factor, but in the prioritisation framework, urban heat is defined as ‘heat exposure’. Loughnan et al. (2013) also identifies areas with a high proportion of aged care facilities as a risk factor, but for the purposes of this framework, aged care facilities, along with medical facilities and schools are classed under ‘behaviour exposure’

What areas are considered to have high behavioural exposure?

Areas of elevated levels of behaviour exposure include locations where day to day activities occur and result in populations being voluntarily or non-voluntarily exposed to excess heat. It includes public locations where many people tend to congregate including:

- Health and community centres (including aged care homes)
- Education centres
- Public transport areas
- Shopping districts
- Parks and recreational areas

Data sources may include local government maps, planning schemes, and public and private service locations. Many of these maps are available in Geographical Information Systems (GIS).

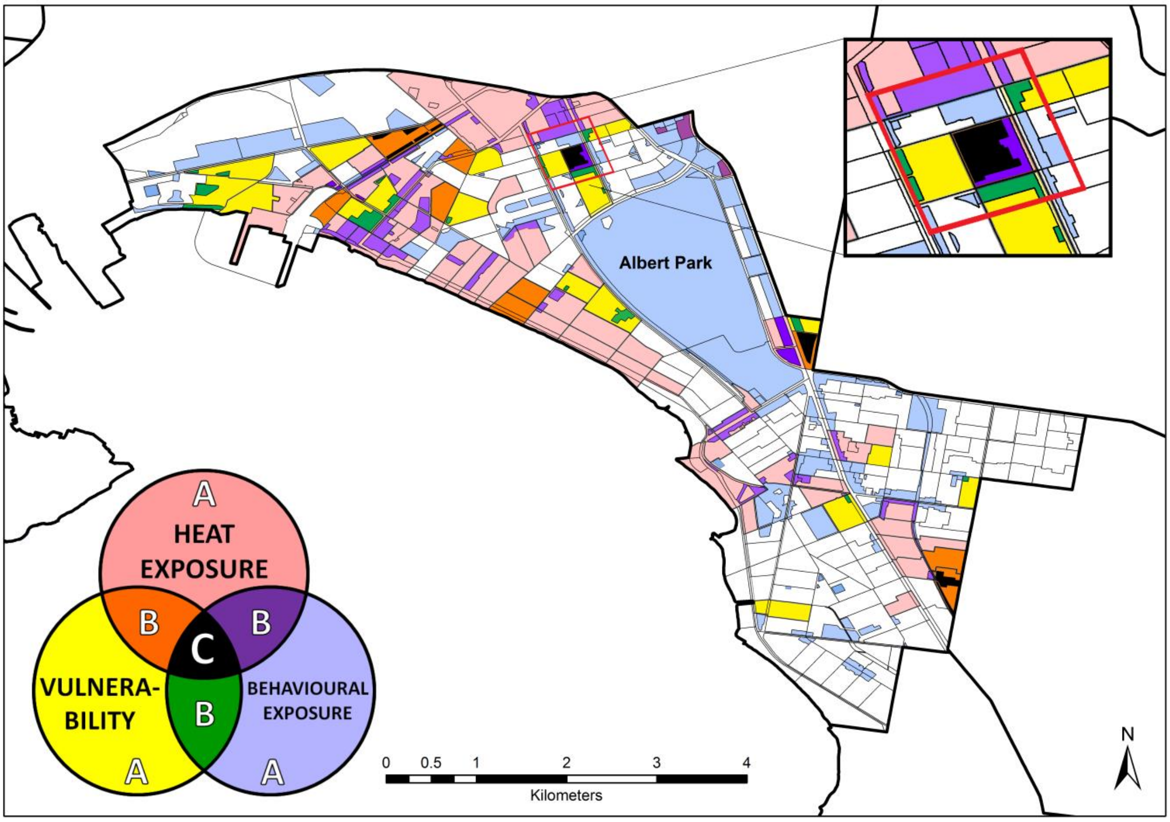

FIGURE 19: Priority neighbourhoods for mitigation of high urban temperature using green infrastructure in the City of Port Phillip. Darker colours (purple, orange and green) represent higher priority locations, and black represents the highest priority locations for heat mitigation and UGI implementation. The inset is an identified priority neighbourhood surrounded by the red box (Norton et al., 2015).

* How does WSUD help?

Water sensitive urban design plays a critical role in mitigating urban heat by providing water to urban vegetation so that it remains healthy, with full canopies that provide shade and sufficient soil water to support tree canopy transpiration. During hot and dry conditions, if soil water is limited, trees may prevent water loss by closing their stomata, meaning they transpire less, thereby being less efficient in their cooling. In a preliminary modelling study, we used a model called MAESPA which can model individual trees, to explore the effect on evapotranspiration of changing soil moisture conditions. For a small olive tree in a tree pit, we compared a) when water was only provided by rainfall (e.g. no kerbside inlet) and b) when water was provided by a larger catchment representing WSUD (kerbside inlet present). We found that when the kerbside inlet was included, transpiration from the tree was much higher, especially during warm and dry conditions as the tree had more water available to access and did not need to restrict water loss. This was important because on the hottest days (e.g. day 56), the Olive tree with the addition soil water available from the road runoff continued to transpire, while the Olive tree without additional water did not.

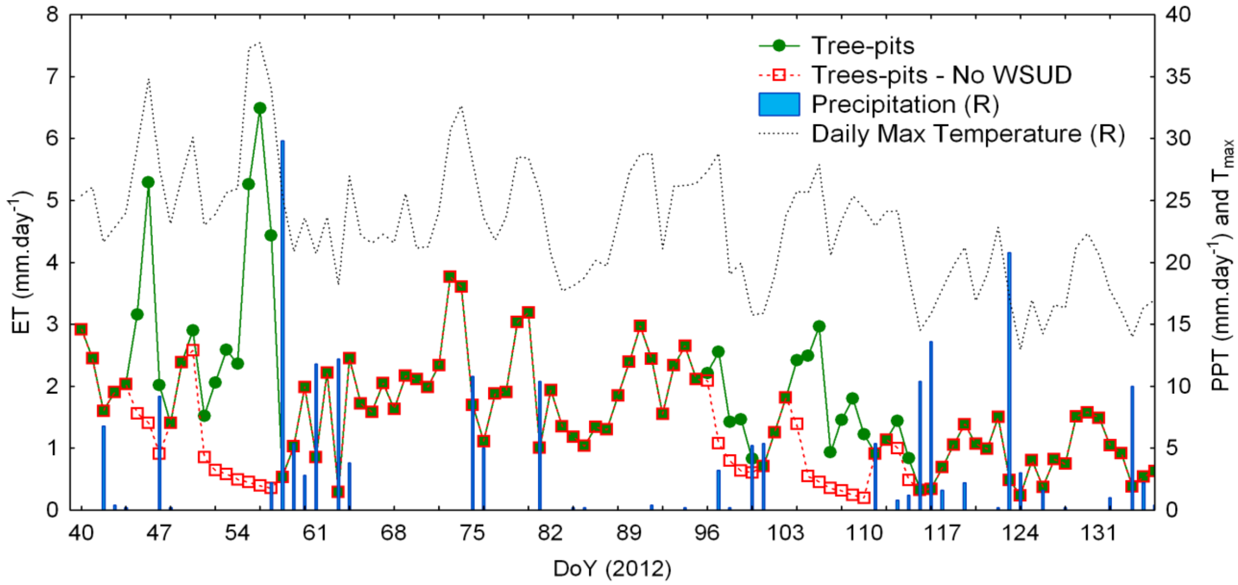

FIGURE 20: Comparison of daily evapotranspiration rate for an olive street tree in a tree-pit that is connected to street runoff, and a tree-pit that is not connect to road surface runoff (No WSUD). Precipitation and daily maximum temperature are also given.

* How should WSUD and greening be implemented?

The implementation of WSUD and urban greening should follow important recommendations that were summarised in (Coutts et al 2012, pg 22):

- Aim to maximize the cooling potential of existing green infrastructure – In many cases, vegetation is already present in the landscape, but to ensure that it is providing a benefit to the urban microclimate, vegetation needs to be well watered and protected. Introducing urban greening when existing vegetation is struggling with limited water availability may not be the most effective approach, especially under a variable and changing climate. Further, urban environments often place additional heat loads and evaporative demands on vegetation, so water is necessary to help support help vegetation.
- Target dense urban environments with little or no vegetation – Highly built-up areas are likely to be hotspots and so need to be tackled as a priority. Introducing urban greening into warm, dry areas surrounding by impervious surfaces will deliver a larger benefit than in an area with existing vegetation. Because of the likely challenging conditions, this greening should be supported by WSUD.
- Harness the cooling and human thermal benefits (HTC) of trees – Trees act as conduits for water loss from the soil to the air via transpiration, effectively acting like evaporative cooler. Trees are especially effective as they support both evapotranspiration and shading. Therefore, trees lead to reduced air temperatures and also improved human thermal comfort by reducing levels of heat stress during the day.
- Aim for many smaller, distributed technologies and features at regular intervals throughout the urban environment – Because of the highly localised cooling effect of WSUD and urban greening, they must be distributed widely throughout the urban environment. Features located at regular intervals where cooling is most needed will deliver a larger benefit than large but isolated features. This also leads to a more widespread increase in soil moisture, and also distributed treatment and retention of stormwater.

- Work with the built environment to accentuate cooling influences – Maximising the benefit of WSUD and urban greening for the investment made requires consideration of the built environment. Tall buildings can block downwind cooling effects, but they can also provide shade negating the need for tree shading. WSUD and urban greening should be strategically designed with the built environment.

* How should WSUD be designed to achieve maximum cooling benefits?

The design of WSUD should incorporate trees and a means of sustainable irrigation whenever possible. Currently, WSUD is designed primarily to meet stormwater quantity and quality objectives. Unfortunately, this may not deliver the greatest benefit for urban cooling. Many WSUD features such as green roofs and biofiltration systems have high infiltration rates which allow for the large capture of stormwater, but they also drain quickly. This means that soil water availability may be low when heat waves occur. This was observed from biofiltration systems in Collingwood, Melbourne where the fluctuations in soil moisture were both high and rapid. As such, when high urban heat occurs, water is not necessarily available for trees, and evapotranspiration will be suppressed.

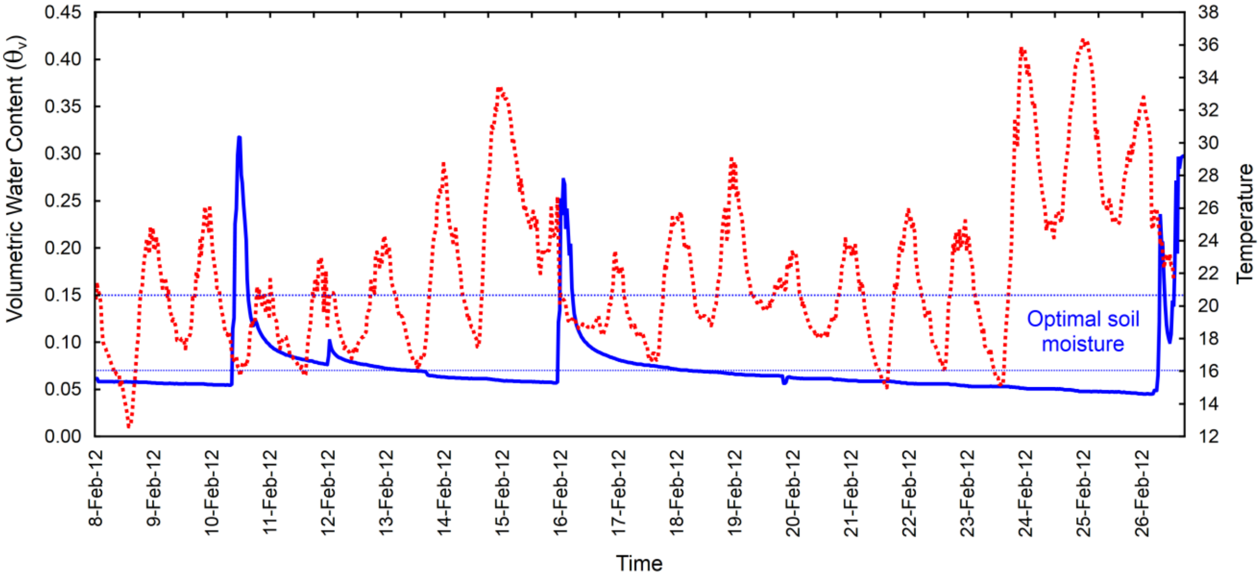

FIGURE 21: Changing soil moisture (volumetric water content) in tree pits in Smith St. Collingwood, and the air temperature at the time in February 2012 (Gebert, 2012). When air temperature was high, the tree pits tended to be dry.

To meet water demand when it is most needed, urban greening and WSUD may need to be supplemented with irrigation from harvested stormwater. Passive irrigation though WSUD will provide higher levels of soil moisture for a longer period of the year than traditional development and drainage, but meeting the needs of the tree during heat events and supporting their cooling capacity will likely require additional water.

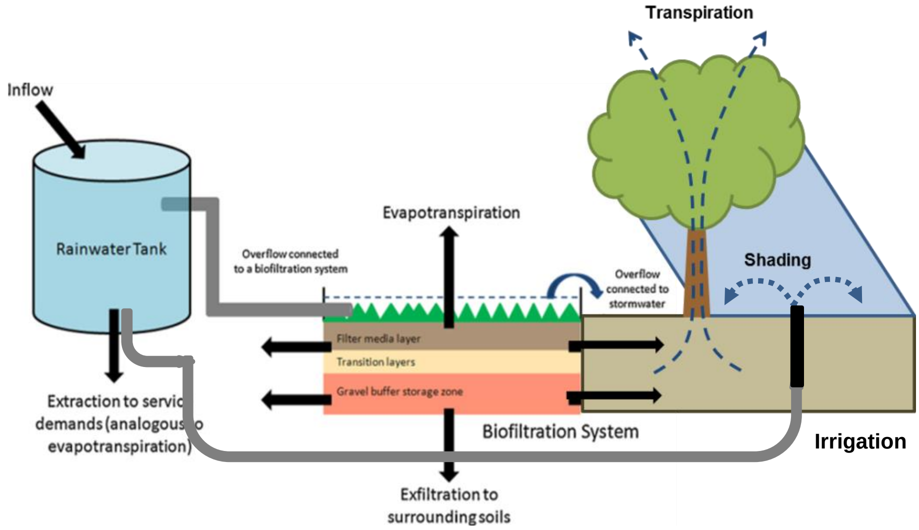

FIGURE 22: (Burns et al., 2012) design of biofiltration systems with potential refinements to enhance evapotranspiration with exfiltration from biofiltration systems to support trees and tank water to provide irrigation to both the biofiltration system and tree.

We applied a similar design in an urban climate model (the Community Land Model – Urban) based on the tree pits in Collingwood, Melbourne. We explored a number of design scenarios around soil type, presence of vegetation, irrigation and the total amount (e.g. percentage cover) of biofiltration systems in the street. The measure of performance was based on the total evapotranspiration rate. Naturally, the evapotranspiration rate increased as the percentage cover of biofiltration systems increased.

- We suggest aiming for a percentage cover of biofiltration systems of up to 35% of total unbuilt surface area, as above this, additional gains in evapotranspiration were minimal.
- Evapotranspiration rates increased by incorporating vegetation as the roots draw more water from the soil,
- Using loam soil produced higher evapotranspiration rates as less water exfiltrates from the system making more water available for evapotranspiration. However, this may mean reduced stormwater treatment efficiency. To offset this, a slightly larger treatment than the minimum suggested (i.e. 5% of the catchment area) may be needed.
- Evapotranspiration is greatest when irrigation is applied, and without irrigation, biofiltration systems at times became dry.

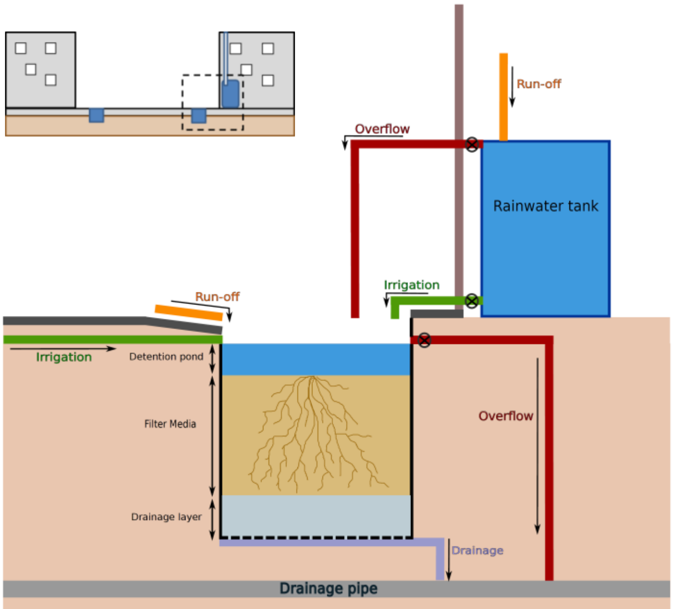

FIGURE 23: Detailed conceptual overview of the lined biofiltration system as implemented in CLMU. The full arrows denote the direction of water transfers while the dashed line refers to drainage of both the filtered and unfiltered water. The three main zones of the BFS: detention pond, filter media and drainage layer are also shown (Demuzere et al., 2014).

SUMMARY

- Implementing WSUD and urban greening into the landscape certainly helps reduce temperatures and improve human thermal comfort, but the placement and design of systems influences their 'benefit'
- Strategic placement of WSUD that is 'fit for place', based on prioritising key areas can maximise returns on investment.
- Trees should be supported by WSUD, and WSUD should include trees where possible.
- Passive irrigation, as well as stormwater harvesting and active irrigation should be considered as a means to support trees.

Won't rainwater tanks typically be empty during heat events when it is most needed?

During extended dry periods, supplies of harvested stormwater may drop. There are a number of responses to this:

- If rainwater tanks are part of a broad suite of WSUD solutions implemented across the landscape, then soil moisture levels should theoretically be higher, leading to a reduced need for irrigation from harvested stormwater. Irrigating with harvested stormwater throughout the year should lead to a larger soil moisture store.

- Using harvested stormwater throughout the year for irrigation essentially offsets potable water consumption. This means that potable water is freed up for use at those times when harvested stormwater supplies are low. Given the microclimatic benefits of irrigating and maintaining healthy vegetation, this is a good investment of potable water and should not be seen as a waste of water.
- Current methods of stormwater storage are constrained by regulations and perceived cost. There are large amounts of space available for small, distributed storage that can be discrete if landscapers, engineers, designers and architects can overcome the constraints by showing the economic and health benefits of such storage.

Couldn’t we just irrigate all of the green space we have?

Many areas of our cities are already quite green, and it is important that our existing green space is valued. This means protecting as much green space as possible, while still allowing urban development to cater for growing populations. Protecting existing green space means sufficient water from sustainable sources must be made available to keep urban vegetation healthy and productive, providing shade and actively transpiring. Irrigation of pervious surfaces is a rapid, controllable method of increasing soil moisture, especially when it is most needed. If urban heat mitigation is a primary objective of investment in WSUD or urban greening, then technologies for water capture, storage and irrigation of trees will be highly beneficial for improving urban climates.

* Won’t widespread implementation of WSUD lead to an increase in humidity?

There is a possible risk that widespread implementation of WSUD could lead to an increase in humidity, and therefore have a negative impact on human thermal comfort. However, much like the existence of the urban heat island, cities also routinely display what could be described as an urban ‘dry’ island. Because of the removal of stormwater and vegetation, urban areas are much dryer, and this is a primary cause of the additional urban heat. Retaining stormwater in the urban landscape (water that landed there but is normally exported away) simply returns the water to the soil similar to pre-development conditions.

When considering human thermal comfort, our work clearly shows that reduction in mean radiant temperature and reductions in air temperature outweigh any negative effects of increased humidity. This does highlight again though the benefit of trees in provided that much-needed shade for urban populations and impervious surfaces. Humidity increases are also less likely to be an issue in drier climates in cities such as Perth, Adelaide and Melbourne. In the cities with higher humidity the major implication will be that the evaporative cooling benefit will be reduced, but this will be outweighed by the thermal benefits of shading where tree canopies are present.

Finally, increasing the humidity can actually have a positive effect with respect to trees. The warmer and drier urban environment actually places a greater evaporative demand on trees than those in many rural areas. In addition to a warm and dry atmosphere, urban trees are often exposed to higher amounts of radiation (e.g. reflected and/or emitted from the ground) and street trees in particular are often isolated. These are harsh conditions for trees and lead to high vapour pressure deficits. In response, trees close their stomata to prevent water loss and can lead to defoliation. Increasing the humidity leads to a reduction in the vapour pressure deficit thereby reducing the evaporative demand and stress on tree canopies, leading to healthier, full canopy trees.

* How much water do we need?

The amount of water required can be dictated by aiming to maintain adequate soil moisture. Soil moisture levels need to be above the wilting point (the point where vegetation can no longer extract water from the soil and the vegetation wilts) and below the field capacity of the soil (the point where the soil is essentially 'full'). Soil moisture should be maintained within the water holding capacity and is the portion of water that can be absorbed by plants. Too little water, and the plants wilt. Too much water and the plants can't access that water anyway, and is unnecessary. So how much water is this in practice? This of course depends on the areal extent of pervious surfaces to be irrigated, but it also depends upon the soil type, atmospheric conditions, and vegetation type:

- The range of soil water contents for accessible plant water varies with soil texture (Figure 24) Maintaining the soil water between the field capacity and wilting point, also known as the 'available water', within the plant root zone will ensure plants have access to adequate water supplies.
- The loss of water from the soil depends on the atmospheric demand where a drier atmosphere has a greater capacity to 'take up water' due to a greater vapour pressure deficit. Evaporative water loss from the soil will be greater under drier conditions.
- The type of vegetation (trees) will influence the uptake of water based on plant physiology including their rates of stomatal conductance and optimal growing conditions in terms of their response to light and CO2 concentrations. While trees act as a conduit for water loss from the soil to the air, their stomatal controls act as a resistance to water loss and if soil water is low, then plants will resist water loss by closing their stomata.

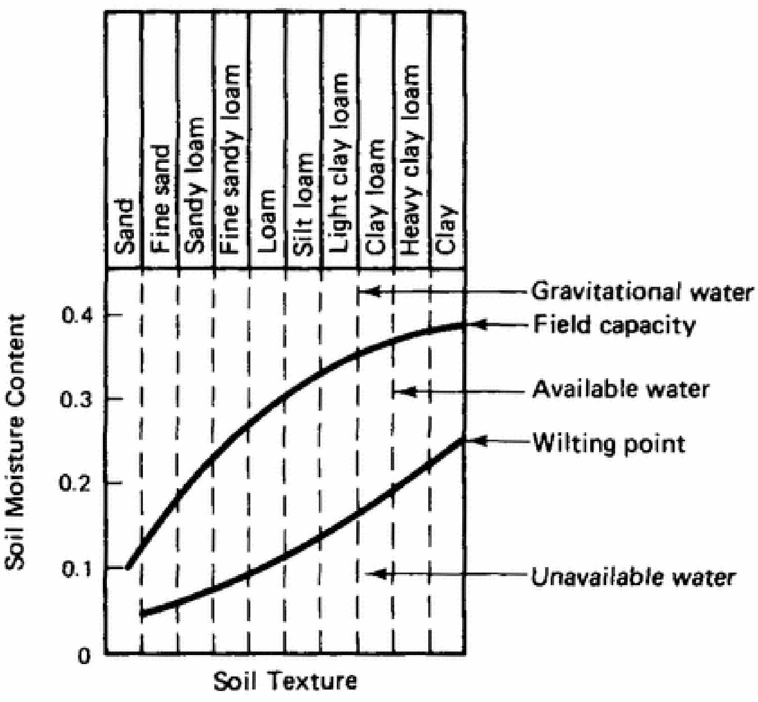

FIGURE 24: Saturated soil drains quickly by gravity until the moisture content (fractional volume of water in the soil) reaches the field capacity. After that, plant roots can extract additional moisture (available water) until the moisture content reaches the wilting point (McCuen, 2004).

Should we plant exotic or native species?

The selection of street trees will no doubt consider factors beyond that of just urban cooling, and the selection of street trees should not be a case of either/or in terms of whether to plant exotic or native tree species. Ideally, a mix of trees should be considered as this builds resilience against future urban climatic changes and other pressures on trees. That said, there are a number of tree characteristics that may result in a greater benefit for urban climates at a range of scales. One way of considering tree characteristics is by considering Plant Functional Types (PFT) and their ability to influence two key processes for cooling: shade and transpiration.

Through a brief literature review, in terms of shade, 'broadleaf' trees rather than 'needle-leaf' trees provide greater benefit because the larger leaf size intercepts more solar radiation. The size, shape and leaf density were also important. Tree canopies that are short and wide, rather than tall and thin, will provide greater areal shade coverage, and denser tree canopies (with high leaf area density) also intercept more solar radiation. While the benefit of shade from trees varies with leaf type and canopy form, the nature of the surrounding urban landscape is also important. For instance, shade trees will be most effective in wide, open streets where shade from buildings is minimal (Coutts et al., 2015), and should be considered in tree placement.

Regarding tree transpiration, this is extremely variable between tree species and plant type, and is influenced by photosynthesis and stomatal conductance rates. Because of this variability, it is only possible to make broad statements about benefits from transpiration. Generally, broadleaf species tend to have higher transpiration rates than needle leaf species. Environmental conditions strongly influence transpiration, and there has not been wide research of the influence of the urban environment on stomatal conductance and urban tree transpiration. While some broadleaf species may have very high transpiration rates, if water availability becomes limited, stomatal conductance rates may be affected. Under these conditions, drought tolerant species and heat tolerant species should be considered.

In summary, a mix of trees should be considered to develop resilience under a range of environmental conditions. If broadleaf species with a high water demand are planted, then these should be prioritised for supplementation with WSUD. It is critical that the shade from trees is maintained for daytime human thermal comfort. A brief table outlining plant functional types in terms of their main cooling mechanisms is provided (Table 6)

TABLE 6: Summary of considerations in Plant Functional Types (PFT) in promoting cooling through the two primary cooling mechanisms of shading and transpiration.

	Shade	Transpiration
PFT considerations	Larger leaf surface areas Higher leaf area and canopy densities	Leaf types (malacophyllous, coriaceous, sclerophyllous, laurophyllous) (from Box, 1996)
Suggested appropriate PFT	Broadleaf species The combination of forms of shorter heights and wider canopies	Broadleaf species of malacophyllous and coriaceous leaf types
Additional influencing factors	Only relevant within urban canyons of low to moderate building shade	Processes are complex

		Broadleaf species show a wide variation in transpiration rates Only relevant in conditions of ample soil water content

How does Project B3.2 'The design of the public realm to enhance urban microclimates' combine with the work and findings of Project B3.1?

Project B3.1 was focussed on observations of the variability in urban microclimate and the impact of WSUD and urban greening on cooling and improved human thermal comfort, and is the focus of much of the work presented here. This work helped to quantify "… the microclimatic influence of harvesting solutions and WSUD at the micro-scale". It also helped to understand some of the key processes determining the development of urban microclimates. Critically, Project B3.1 has provided a solid foundation for the work of Project B3.2 by providing a unique collection of datasets that can be used in the validation of a variety of urban climate models operating at a range of scales. Some of these have been touched on here including SOLWEIG and MAESPA (operating at the micro-scale) and the Community Land Model – Urban (operating at the local-scale). They have also been used in developing the microclimate component of the CRCWSC Toolbox.

Project B3.2 has a focus on scenario modelling to "help inform the design of the public realm to enhance urban microclimates". The observations and understanding of processes from Project B3.1 will underpin the scenario modelling of Project B3.2. Critically, these datasets act as an important tool for model validation so we can have confidence in the scenarios of urban design. Having understood the potential cooling effects of different WSUD elements, informed design scenarios can be developed. This will inform and support urban planners and designers in the development and implementation of strategies that mitigate excess urban heat and reduce heat stress.

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