CRC for
Water Sensitive Cities

Estimating the economic benefits of Urban Heat Island mitigation – Biophysical Aspects

Final Report (Work Package 6)

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Estimating the economic benefits of Urban Heat Island mitigation – Biophysical Aspects
Final Report (Work Package 6)
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1 Introduction

This report documents the work undertaken by E2DESIGN and Monash University in assessing the impact of different policy settings on the biophysical environment, including urban warmth, of a de-identified case study suburban landscape in Melbourne[1]. The partner report produced by RCMG "Estimating the economic benefits of urban heat island mitigation – economic analysis", assesses and quantifies the economic benefits of the reduced summertime heat produced by those settings and is available through the CRC for Water Sensitive Cities.

2 Scenario Descriptions

Four hypothetical scenarios were chosen to represent four policy stances relating to WSUD and IWM investment. These are:

- Scenario 1: No IWM regulation. i.e. no stormwater quality improvement or potable water saving targets or measures in place.
- Scenario 2: Current IWM policy setting, incorporating landscape features to meet stormwater quality for residential subdivisions that are required under Clause 56.07 of the Victorian Planning Provisions as well as requirements under the 6 Star Building Code (potable water saving targets).
- Scenario 3: Potential future IWM policy setting: representing the introduction of a 60% flow volume reduction target in addition to water quality targets for residential subdivisions.
- Scenario 4: Targeted UHI mitigation scenario: this analysis represents IWM and landscape initiatives necessary to achieve significant reduction in the UHI effect.

Further descriptions of the elements peculiar to each scenario are included in following sections.

The project modelling was carried out over the theoretical future development of a greenfield subdivision area on the outskirts of western Melbourne. The spatial representation is shown in Figure 1 below. The development zones shown were digitised into GIS layers to represent, urban residential, roads, commercial, industrial, non-irrigated open space and irrigated open space. These layers were imported into the CRCWSC Scenario Tool (https://watersensitivecities.org.au/) which was used as the interface to set up further parametrisation of zones and create the gridded dataset required for interface to the microclimate model.

For each scenario, MUSIC modelling ascertained the particular design requirements necessary to meet the IWM regulation objectives. These were translated into urban design characteristic input parameters that were used in the microclimate modelling. Two microclimate models were considered for this modelling task, SURFEX[2] and TARGET[3], but because of time and funding constraints, only TARGET, a model developed at Monash University for the CRCWSC was used here. However biophysical parameters for both models were developed, so that SURFEX could be used in the future, should the funds and opportunity arise.

[1] The approximate coordinate of the location is -37.580060, 144.735870. Note that the development plan features and characteristics were solely hypothetical and developed for use in this academic simulation exercise only.
[2] Masson, V. et al, 2013 "The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes", Geoscientific Model Development, 6, 929-960, https://doi.org/10.5194/gmd-6-929-2013
[3] Broadbent, A. et al, 2019 "The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET v1.0): an efficient and user-friendly model of city cooling", Geoscientific Model Development, https://doi.org/10.5194/gmd-2018-177, 2018

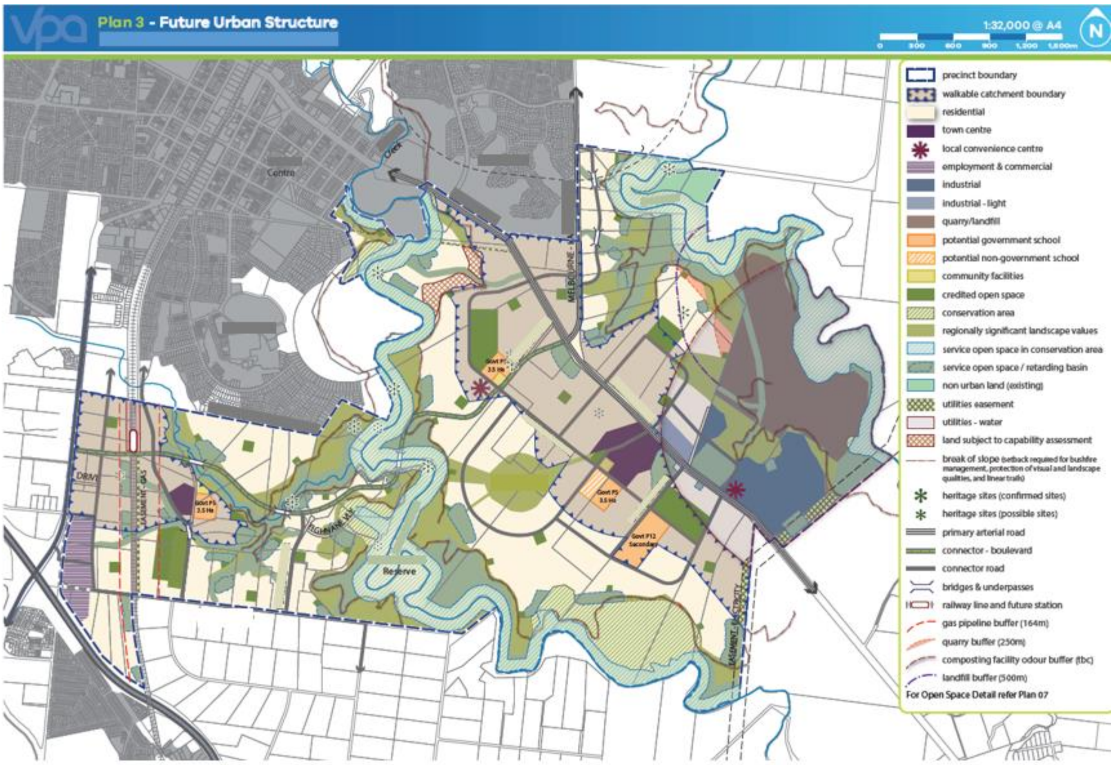

Figure 1 – The greenfield case study area in outer Melbourne.

The biophysical parameters obtained from the modelling approach are summarised in Table 1 below. Further detailed description for each is included in the following paragraphs.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
<u>Urban Residential</u>				
Roof	60% of lot	60% of lot	60% of lot	60% of lot
Other Impervious	20% of lot	20% of lot	20% of lot	20% of lot
Pervious area	20% of lot	20% of lot	20% of lot	20% of lot
- **Low veg on lot**	17% of lot	17% of lot	17% of lot	15% of lot
- **Trees on lot (high veg)**	3% of lot	3% of lot	3% of lot	5% of lot
- **Irrigated grass**	30% of all lots	30% of all lots	60% of all lots	100% of all lots
- **Dry-grass**	70% of all lots	70% of all lots	40% of all lots	0 % of all lots
- **Raingarden**	none	none	2.7 m^2 per lot	2.7 m^2 per lot

- Infiltration trench	none	none	20 m^2 per lot	20 m^2 per lot
Trees on lot	none	none	none	1 tree on lot per lot – 22.8 m^2
Tanks	0 % of lots	30 % of lots	100% of lots	100% of lots
- Demands on rainwater storage in tanks	outdoor	Toilet + outdoor	Outdoor, toilet, laundry + hot water	Outdoor, toilet, laundry + hot water
Pervious soil moisture - unirrigated	9.6%	9.6%	9.6%	9.6%
Pervious soil moisture - irrigated	17.6%	17.6%	27.3%	~40.0%
Open Space				
Irrigated open space – typical annual values	1.5 - 3 ML/Ha	1.5 - 3 ML/Ha	3 - 5 ML/Ha	3 - 5 ML/Ha (or higher)
Water bodies	No wetlands	Wetlands	Wetlands + evapotranspiration fields	Wetlands + evapotranspiration fields
Road Reserve (FI = 70%)				
Trees on urban streets	1 tree /lot frontage* 9.6 m^2	1 tree /lot frontage* 9.6 m^2	1 Passively irrigated tree/lot (> canopy)* 22.8 m^2 per tree	2 Passively irrigated trees/lot (> canopy)* 22.8 m^2 per tree
Commercial and Industrial				
Fraction impervious	90%	90%	90%	80%

Table 1 – Raw biophysical parameters for microclimate modelling

2.1 Scenario One

No IWM regulation. i.e. no stormwater quality improvement or potable water saving targets or measures in place.

Landscape features in the absence of any regulation for IWM (e.g. Best Practice Environmental Management (BPEM), Building Codes) would include street trees with no irrigation, no precinct scale green infrastructure and 0% uptake of on-lot rainwater tanks. Even though the policy stance for this scenario is a zero on-lot tanks and no WSUD, it is assumed realistic that 30% of households would still irrigate private gardens using potable water. It is assumed that in the heatwave scenario, water restrictions will negate the use of daytime irrigation, but a certain demographic of the population will still irrigate in allowed times using potable water.

This scenario and Scenario 2 provide baselines from which the other scenarios can be compared. A typical lot layout with urban design features is shown in Figure 2 below:

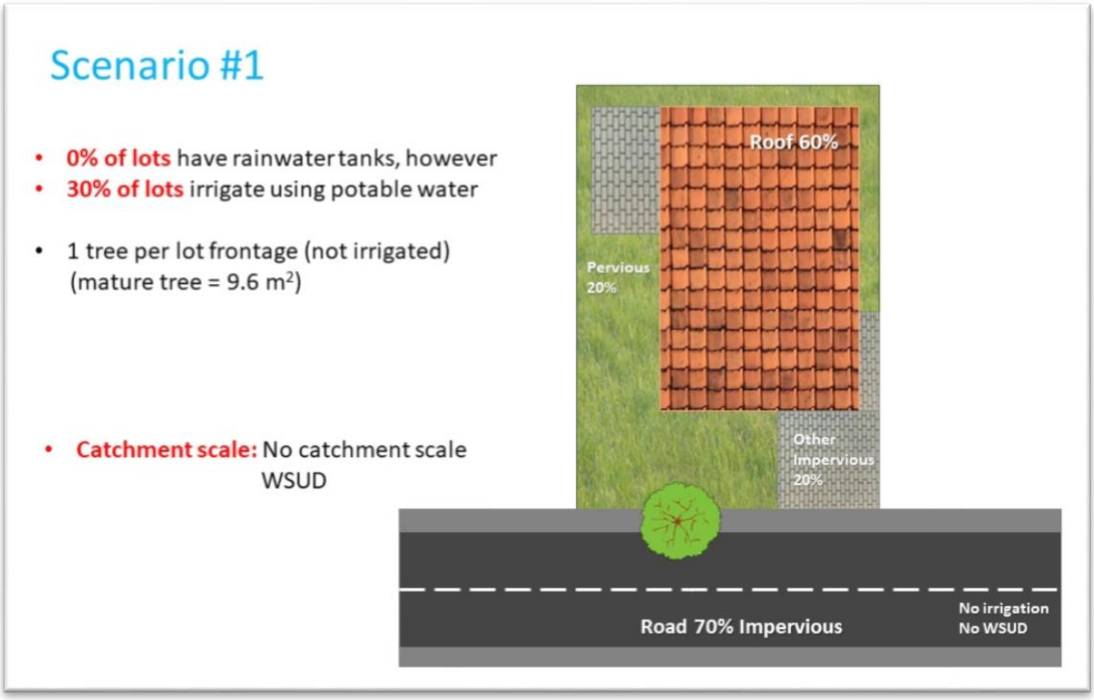

Figure 2 – Typical modelled lot – Scenario #1.

2.2 Scenario Two

Current IWM policy setting, incorporating landscape features to meet stormwater quality for residential subdivisions that are required under Clause 56.07 of the Victorian Planning Provisions as well as requirements under the 6 Star Building Code (potable water saving targets).

Landscape features required to comply with the current regulatory settings (Clause 56:07 of the Victorian Planning Provisions and 6-star building code) would include street trees with no irrigation, precinct scale wetlands designed to achieve best practice stormwater pollutant load reductions and a 30% uptake of rainwater tanks used for toilet flushing and to irrigate private gardens. This scenario will explore the value of current UHI mitigation compared to no regulation.

The Scenario 2 policy setting for Clause 56.07 requires the design to meet the current best practice performance objectives for storm water quality as contained in the Urban Stormwater – BPEM Guidelines (Victorian Stormwater Committee 1999), requiring the following stormwater quality improvement targets to be achieved for all residential subdivisions:

- 45% reduction in total nitrogen loads,
- 45% reduction in total phosphorous loads,
- 80% reduction in total suspended solid loads.

In this assessment stormwater treatment wetlands were sized for each sub-catchment throughout the case study area and included in the surface gridded dataset for the microclimate model.

The 6 Star Building Code requires new homes to include the installation of either a solar hot water system or a rainwater tank for toilet flushing[4]. For the purposes of this assessment it is assumed that 30% of new houses choose to install a rainwater tank (over solar hot water) to achieve 6 Star rating. According to the ABS, some 27% of Victorian homes have a rainwater tank installed[5], and 86% of Victorian dwellings have their own garden[6]. These figures are somewhat arbitrary in terms of specifying an irrigation rate as some dwellings without tanks may still use potable water to irrigate their gardens, and not all garden owners will irrigate consistently if at all.

The tanks were assumed to be 5KL, with 80% (219 m^2) roof catchment to the tank. The demand for tank water in Scenario 2 is both toilet flushing and outdoor irrigation. The toilet flushing demand may affect the irrigation rate, as it assumed irrigation will not occur by potable water after tank water runs out. 100% of pervious area on-lot is assumed irrigated for those lots that irrigate (30% of lots). Interestingly, if tank water only is used for irrigation (i.e. no potable top-up and no irrigation by potable water), it may be possible to see a reduction in irrigation rates (and therefore a reduction in cooling effects) in this scenario due to the introduction of roof water harvesting policy, especially if other internal household demands are being met as priority. In this modelling exercise, we have assumed the same irrigation rate between Scenarios 1 and 2, as the data are simply not available to tease out these intricacies of behavioural usage patterns.

A recent report on water use for a number of utilities in the Melbourne region[7], suggests the typical average irrigation rate for residents of the local council is approximately 77 L/hh/day. This irrigation rate was used as a tank demand in MUSIC with a seasonal distribution. The re-use supplied was then applied to a soil model, to calculate soil moisture estimates for irrigated as compared to non-irrigated soils.

[4] https://www.parliament.vic.gov.au/images/stories/committees/enrc/future_water_supply/Submissions_57_110/098_Institute_of_Public_Affairs.pdf, August 2008, viewed 14/11/2017
[5] http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4602.2Chapter400October%202011
https://www.parliament.vic.gov.au/images/stories/committees/enrc/future_water_supply/Submissions_57_110/098_Institute_of_Public_Affairs.pdf, August 2008, viewed 14/11/2017
[6] http://www.abs.gov.au/ausstats/abs@.nsf/Products/4602.2~Oct+2009~Chapter~Gardens%20and%20Swimming%20Pools, viewed 17/11/2017
[7] https://waterportal.com.au/swf/images/swf-files/10tr5---001-melbourne-residential-water-use_final_report.pdf

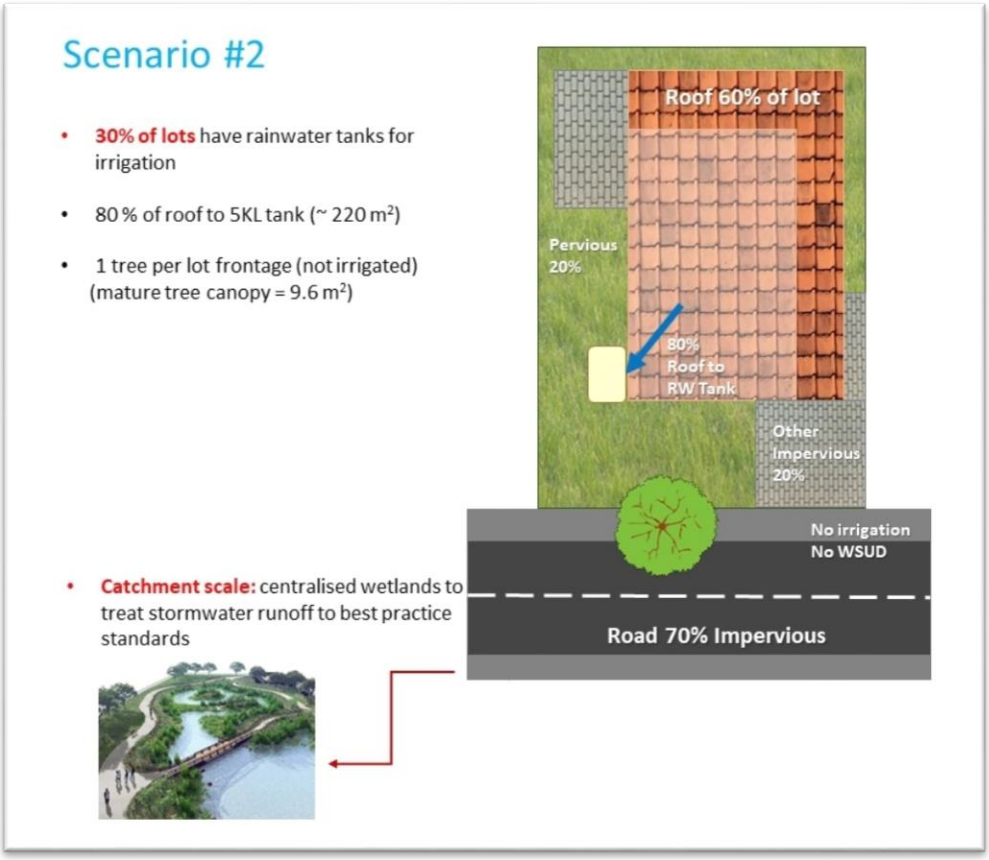

Figure 3 – Typical modelled lot – Scenario #2

2.3 Scenario Three

Potential future IWM policy setting: representing the introduction of a 60% flow volume reduction target in addition to water quality targets for residential subdivisions.

Landscape features used to deliver the anticipated changes to IWM regulation for both BPEM and Building Codes, to achieve a 60% reduction in mean annual flow volumes, include a range of initiatives integrated into the urban landscape at the lot, streetscape and precinct scale of development. Initiatives included the inclusion of 100% uptake of rainwater tanks. This scenario assumed roughly double the rate of lot irrigation as previous scenarios, with 60% of households irrigating pervious areas in private gardens. That is, even though 100% of lots have tanks, not all households will choose to irrigate (and not all households have gardens). The tank is also plumbed to other internal demands such as hot water, laundry and toilet flushing. Tank overflow and other impervious areas run off to infiltration trenches and raingardens located on each lot. Each property has one passively irrigated tree located on the street. In this assessment, stormwater treatment wetlands were sized for each sub-catchment throughout the case study area (as per Scenario 2), and additional evapotranspiration fields were located along the waterway corridors to achieve the flow reduction target.

The inclusion of raingardens and infiltration trenches on-lot has complicated implications for the soil moisture parameters for modelling. The high infiltration/exfiltration rate media used in this infrastructure may mean that (depending on the timing of a rain event) the soil moisture value may actually be less than a comparative area of irrigated grass. This is discussed further below. In context of the uncertainty in the estimation of irrigation rates in terms of number of households irrigating and irrigation volumes, for the purposes of this modelling exercise, the soil moisture value for the irrigated lots in Scenario 3 is assumed the same as that of irrigated pervious areas in Scenarios 1 and 2. For the 40% of lots that don't irrigate, the soil moisture value used in the microclimate model (over the 2 day heat wave time period used) is assumed equal to that for unirrigated grass in Scenarios 1 and 2.

In each scenario trees are planted in the urban streetscape at a rate of approximately 1 per lot. However, for this scenario, the addition of passive irrigation for trees in the streetscape will see an increase in the size and health of the tree canopy cover. The relationship used for the increase in tree canopy cover is described in Appendix A.

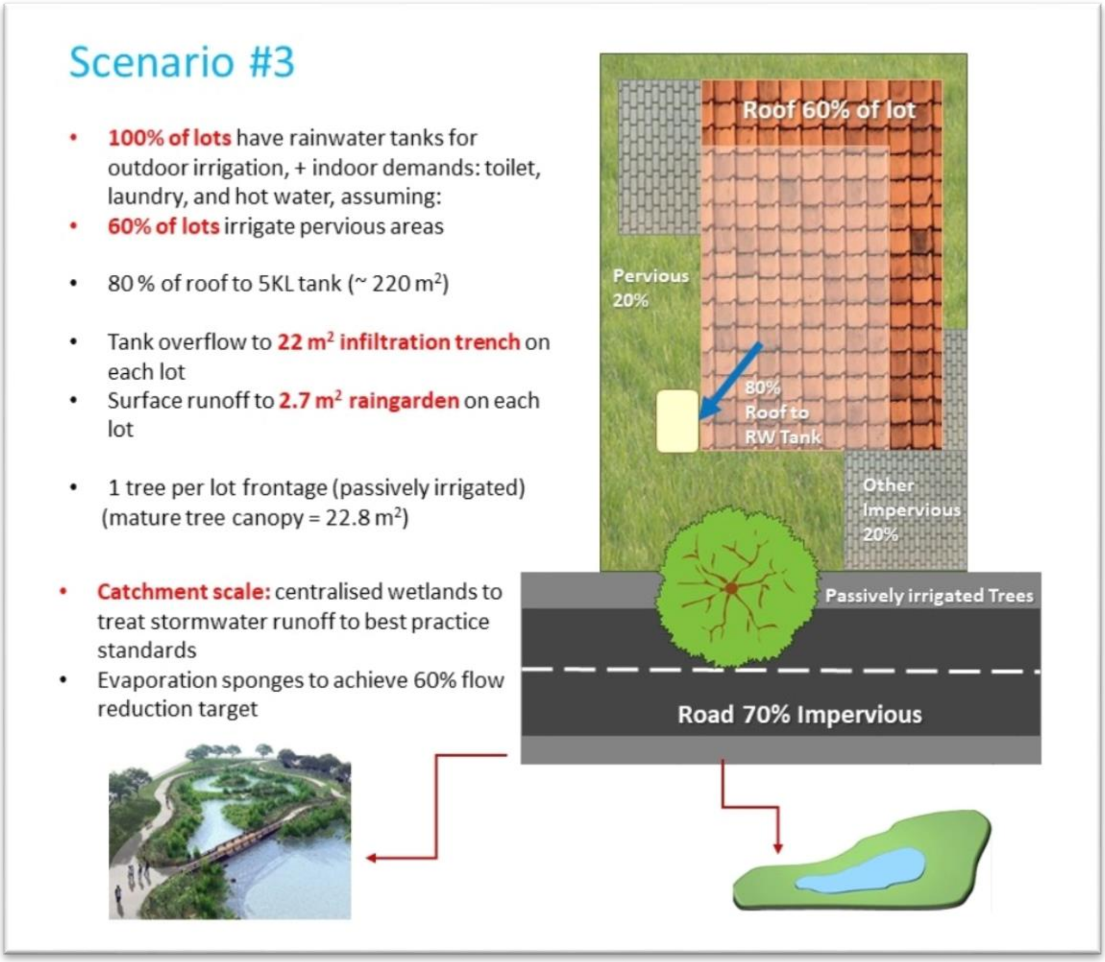

Figure 4 – Typical modelled lot – Scenario #3.

2.4 Scenario Four

IWM required to achieve targeted UHI mitigation impact.

This scenario models the landscape features that are required to deliver substantial summer cooling (as much as 2˚C) at the residential scale. The scenario includes:

- Minimum of one mature tree retained on each lot,
- 2 trees per lot on street frontage
- 100% of lots with tanks and outdoor irrigation
- A higher soil moisture value

Further measures that could be taken include enforcing an impervious surface fraction limit to residential blocks, and enforcing the use of surface treatments with a high albedo (such as white paint for roofs).

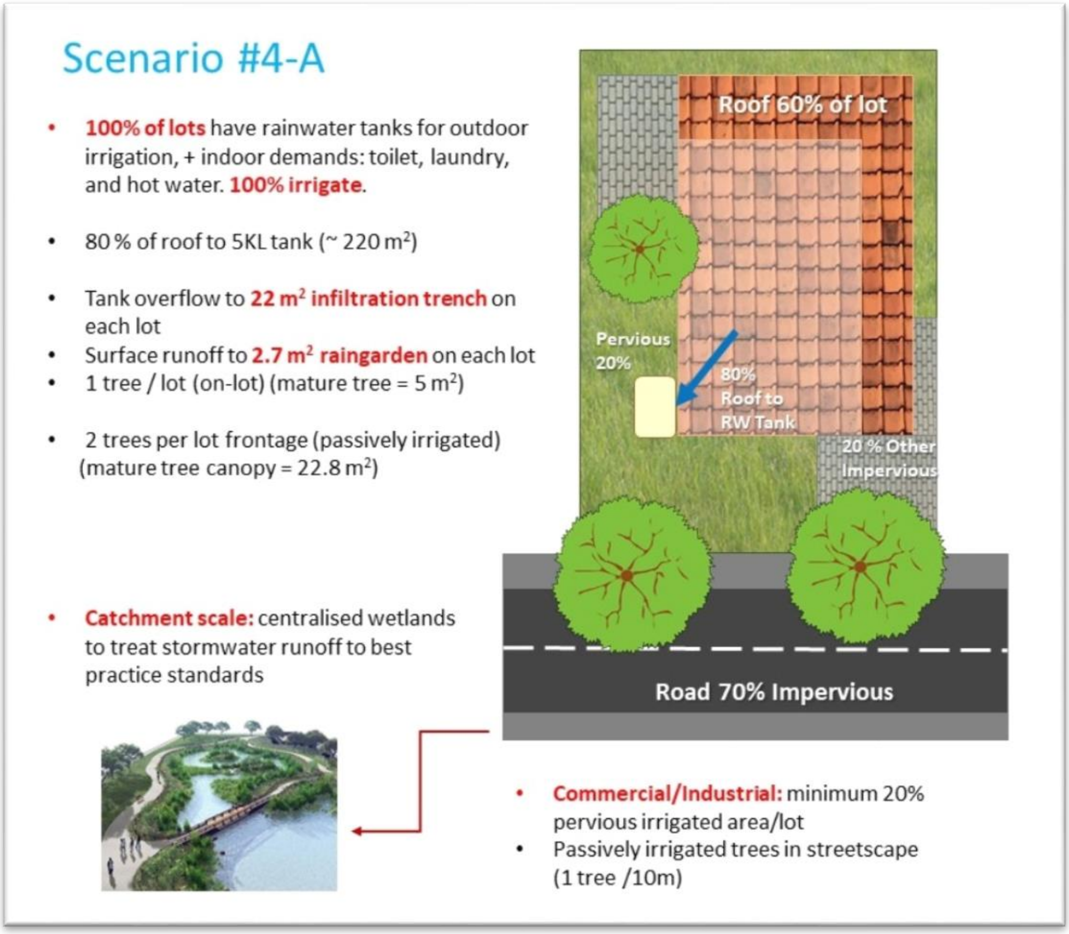

Figure 5 – Typical modelled lot – Scenario #4.

2.5 Soil Moisture Modelling

MUSIC models of a typical lot were set up to provide an estimate of soil moisture for each scenario. The microclimate modelling requires soil moisture estimates for both irrigated and unirrigated soils. MUSIC can provide a time series of soil moisture storage values for pervious source nodes. For Scenario 1, these data were extracted and analysed to find the mean average daily soil storage value for each month of the year (over the data timespan from 2002-2014), as shown in Figure 6 below.

For Scenarios 2 and 3, the pervious soil store for the percentage of lots that irrigated pervious areas was estimated via the following methodology:

- A single lot model was created, with 80% of roof area to a 5KL tank,
- An irrigation rate of approximately 77 L/household/day was used as a tank demand in MUSIC with a 'PET-Rainfall' distribution,
- The time series of re-use supplied was then transformed to a mm/day application rate for the pervious area size on the lot and added to the original rainfall time series,
- The new climate data including irrigation rate were then run with the pervious source node and soil moisture store time series extracted,
- Soil moisture estimates for irrigated as compared to non-irrigated soils, were compared, as per Figure 6.

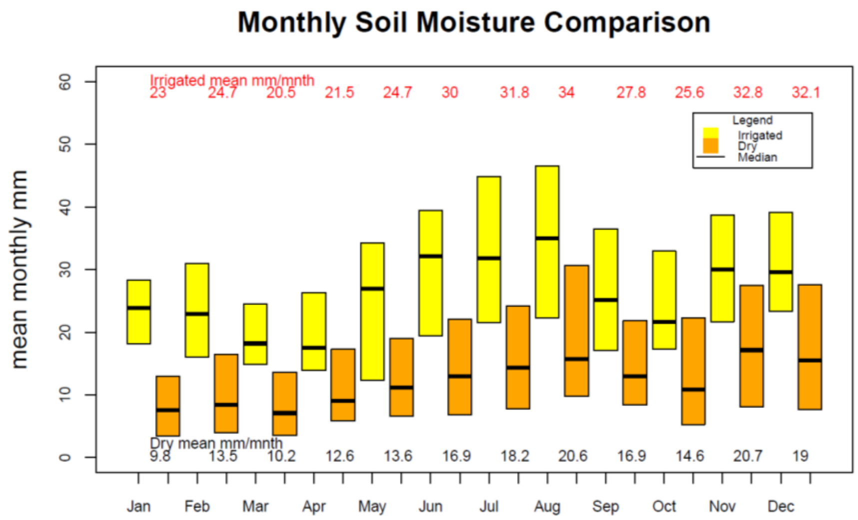

Figure 6 - Soil moisture (mean daily mm), comparison: irrigated and non-irrigated

The climate model is to be run over February, so the mean February values of 24.7 and 13.5 mm for irrigated and non-irrigated landscape have been taken. The soil profile is modelled as a 140mm depth, so these figures equate to 17.6 and 9.6% soil moisture respectively.

For Scenario #3, the additional raingarden and infiltration trench on-lot was modelled in MUSIC. The design intention of the raingarden and infiltration trench is to capture and infiltrate water, in order to reduce runoff volumes leaving the lot. The soil properties facilitating this (higher hydraulic conductivity through the constructed media, and exfiltration through the base of the system) have a corollary effect of reducing mean daily soil moisture compared to an average area of irrigated grass. The pervious area node in MUSIC (used to model irrigated and non-irrigated grass) represents the movement of water through a typical column of soil taking into account soil moisture tension and other parameters. In comparison to the raingarden and infiltration trench, the soil model represents the slower response between moisture entering and leaving the soil profile (either through evapotranspiration or deep seepage to groundwater). This results in a comparatively higher average soil moisture value compared to raingardens and infiltration trenches where the water 'loss' response is more rapid. Due to this rapid response, the WSUD infrastructure on non-irrigated lots has been assigned the same soil moisture value as non-irrigated grass in Scenarios 1 and 2. The irrigation rate for irrigated lots is likewise assumed the same as for irrigated areas in Scenarios 1 and 2.

The other comparative change in Scenario 3 in relation to Scenarios 1 and 2 is that irrigated public space (parks, sports ovals) will experience a greater level of irrigation due to stormwater harvesting and re-use. The irrigation rate used was 3.8 ML/Ha/yr (or 380L/m^2, as determined by a seasonal analysis of optimal irrigated rate for a typical turf for this region. The resulting mean soil moisture distribution is shown in Figure 7 below.

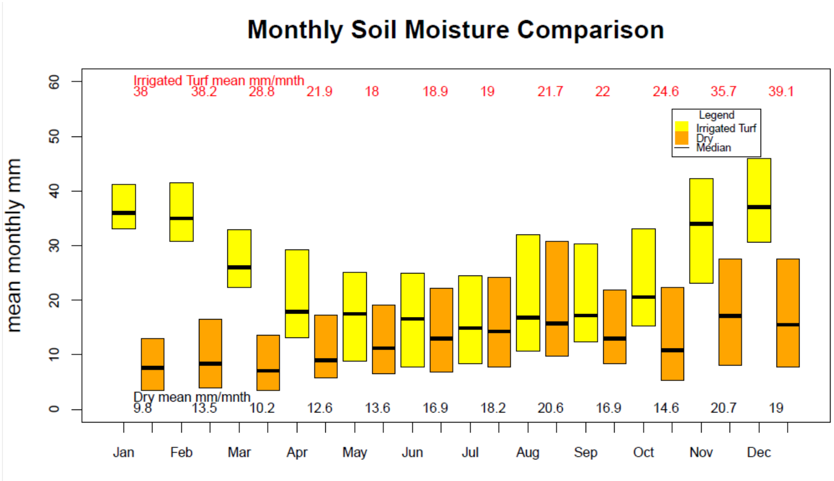

Figure 7 - Soil moisture (mean daily mm), comparison: sports fields irrigated at optimal rate to unmanaged soil

A limitation of the SURFEX micro-climate modelling tool, is that soil moisture for irrigated soils is a global parameter, meaning for each model run there is only one value for all irrigated areas across the model calculation domain. Therefore, the mean value of 38.2 mm (or 27.3%) has been suggested for all irrigated areas in Scenario 3, including on-lot irrigated pervious and irrigated open space.

3 Modelling the Urban Heat Island

3.1 The Modelling Approach

TARGET (The Air-temperature Response to Green/blue-infrastructure Evaluation Tool) was developed specifically for the CRCWSC by Monash University researchers and is designed for efficiency and ease of use, with less input data required than other urban climate models[8]. TARGET can be used to model street level air temperature at fine spatial scales (e.g. at 30 m), meaning it can be used at the street, precinct, or city scales. The model balances realistic representation of physical processes against computational efficiency. Comprehensive evaluation[9] shows that TARGET can reproduce the magnitude and patterns of both air and surface temperature within suburban environments.

The four scenarios described in the sections above each represent a different level of WSUD intensity, with associated levels of vegetation, perviousness and water availability that ultimately affect the surface energy balance and drive the near-surface climate. These differences are then reflected in different thermal and moisture regimes in the local microclimate, with greater urban warmth associated with high levels of impervious surface and reduced vegetation and moisture. In this study, the modelling domain for each scenario is at a resolution of 30m, with a total of 80,000 grid points being used to simulate the case study area.

The land surface categories in TARGET are roof fraction, road fraction, concrete fraction, water fraction, vegetation/tree fraction, dry grass fraction and irrigated grass fraction. For each WSUD scenario the total fraction of each land surface type for the whole modelling domain is shown in Table 2. The proportion of irrigated grass and vegetation are higher and the dry grass fraction is lower in Scenario 4 compared to Scenario 2 indicating

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[8] Broadbent, A. et al, 2019 "The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET v1.0): an efficient and user-friendly model of city cooling", Geoscientific Model Development, https://doi.org/10.5194/gmd-2018-177, 2018

[9] Ibid

more WSUD in the landscape. The average fractions of the land surface categories add up to more than 1 for the Scenarios (Table 2), but for each individual grid point, the sum of the fractions is 1.

Land Surface Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Roof Fraction	0.12	0.12	0.12	0.11
Road Fraction	0.08	0.08	0.08	0.08
Concrete Fraction	0.03	0.03	0.03	0.03
Water Fraction	0	0.08	0.08	0.08
Vegetation/Tree Fraction	0.02	0.02	0.06	0.09
Dry Grass Fraction	0.73	0.73	0.71	0.70
Irrigated Grass Fraction	0.03	0.03	0.04	0.05

Table 2 - Parameters used for TARGET microclimate model, derived from Table 1

3.2 Climate Scenarios

Three different climate scenarios were developed to assess the effectiveness of WSUD during a cool summer's day, a mild summer's day and an extreme summer's day. Half hourly meteorological data from Melbourne Airport weather station, the closest weather station to the case study area, were input to the TARGET model. The meteorological variables used were 2m air temperature (˚C), relative humidity (%), wind speed (km/hr), surface pressure (hPa), total incoming shortwave radiation (W/m^2) and total incoming longwave radiation (W/m^2). The three days for each of the climate conditions (cool, mild and extreme) were chosen for simulation due to high levels of clear sky, which improves the model performance. The dates simulated are in Table 3, where the mild and extreme scenarios contain two of the same dates.

Scenario	Dates
Cool	01/02/2005, 10/02/2009, 08/02/2012
Mild	02/01/2011, 05/01/2011, 02/01/2011
Extreme	06/01/2009, 06/01/2009, 07/01/2009

Table 3 – Days simulated for cool, mild and extreme conditions

In total, twelve simulations were run combining every permutation of the four WSUD scenarios and three climate scenarios.

3.3 Results for the Whole Domain

The area-averaged daily difference in temperature between WSUD Scenarios 1,3,4 and the control case Scenario 2, are shown for each climate scenario in Table 3. Scenario 3 produced the most cooling in each climate scenario compared to the base case of Scenario 2, followed by Scenario 4. This was unexpected and suggests that for the whole domain the highest level of WSUD does not produce as much cooling throughout the three simulated days. However, the cooling produced in these simulations averaged over day and night is extremely small, and does not necessarily reflect physical processes. There was no difference in temperature between Scenarios 1 and 2.

Scenario difference	Cool (˚C)	Mild (˚C)	Extreme (˚C)
Scenario 1 minus Scenario 2	0.0	0.0	0.0
Scenario 3 minus Scenario 2	–0.04	–0.03	–0.03
Scenario 4 minus Scenario 2	–0.02	–0.01	–0.02

Table 4 - The difference in 2 m average daily air temperature between the WSUD scenarios for each climate scenario for the whole domain (case study area)

Overall, the WSUD implemented in Scenario 3 can reduce the 2m air temperature by 0.04˚C over the whole diurnal cycle during cool summer days, and by 0.03˚C during mild and extreme summer days. The noteworthy result is that WSUD is most effective during a cool summer day. To investigate this result further, simulations were performed for each climate scenario, where the whole domain consisted of one land surface category. This was to understand how each land surface type responded to the cool, mild and extreme summer days.

By comparing Figures 8a and b it can be seen that during the cool days there is a clearer difference in temperature between the warmest land surface categories: road, concrete and dry grass. In contrast, during extreme days the differences are much smaller between the categories. Reasons for this are unclear, but may relate to the much higher wind speeds and turbulence on the extreme days washing out the 2m air temperature differences.

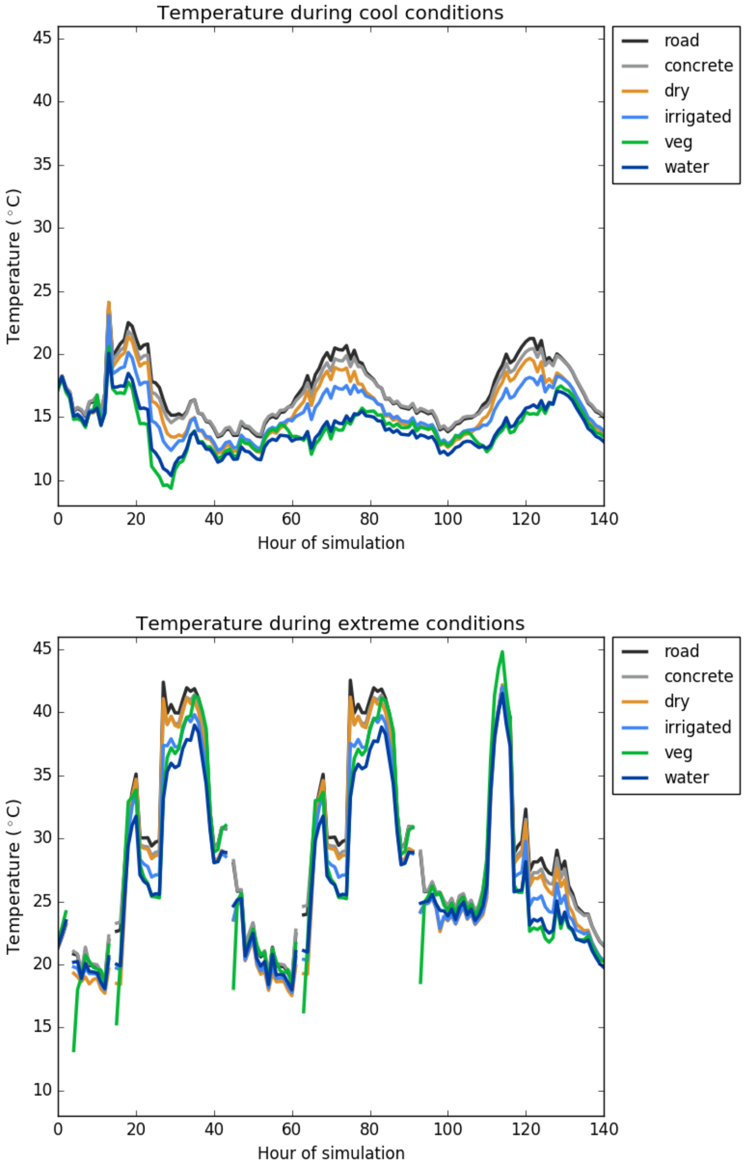


Figure 8 - The 2m air temperature of each land surface category during the three (a) cool and (b) extreme summer days. Missing points are from missing input data.

3.4 Smaller Representative Suburban Area

Averaging results over the whole domain and over the whole diurnal cycle is not necessarily representative of what a person in the case study area is likely to experience, particularly since a large proportion of the modelling domain is unirrigated grassland. Therefore, we conducted analysis on a smaller representative urban portion of the domain, focused on a residential area (highlighted in Figure 9). All results discussed below refer to this more representative urban area.

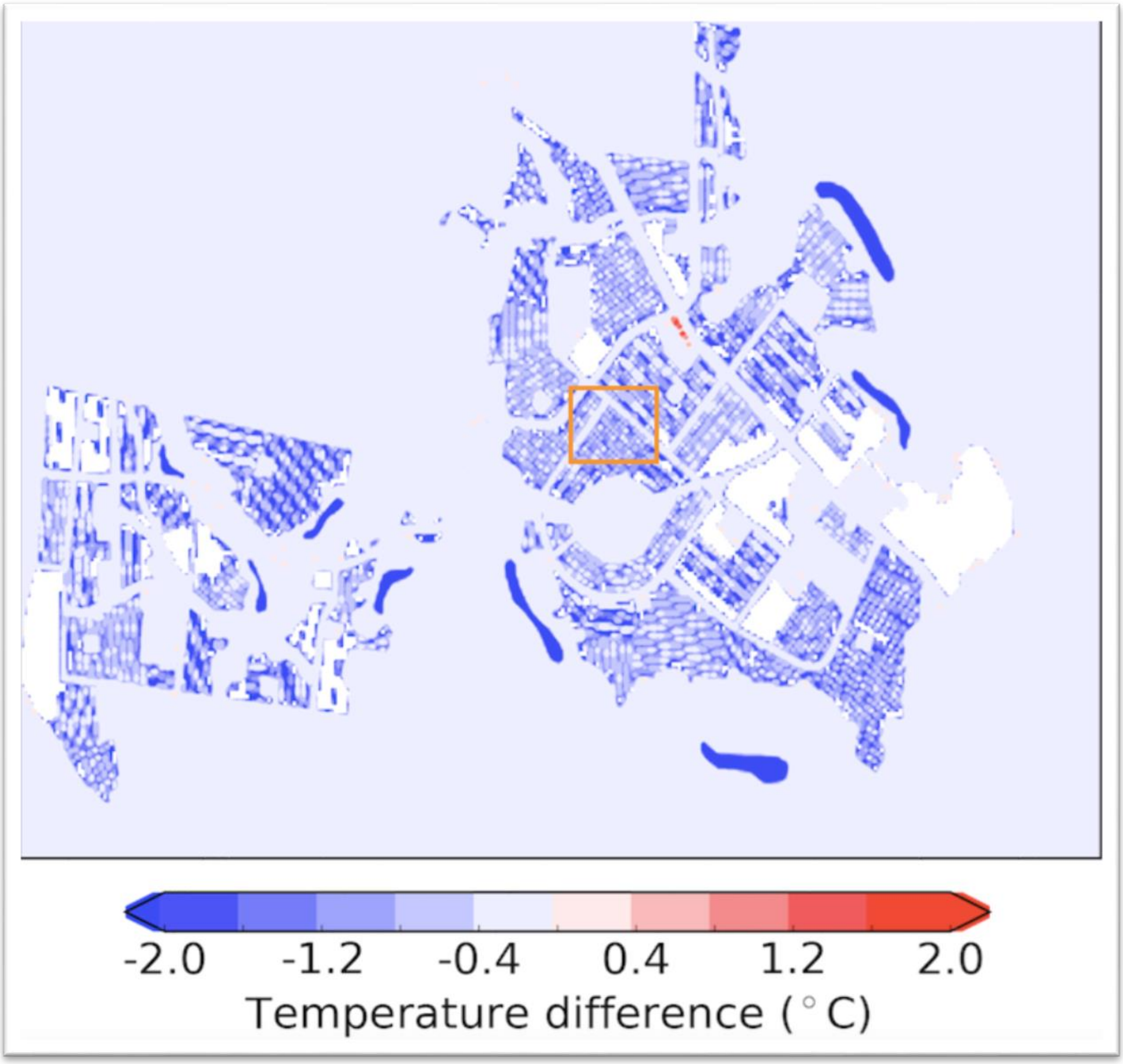


Figure 9 - The 2m air temperature difference between Scenario 4 and Scenario 2 for the whole domain (midday - cool summer conditions), with the orange box indicating the smaller representative residential area.

In this case, much more relevant to the residential population, average daily differences in 2m temperature between Scenarios 1, 3, 4 and Scenario 2 - the control case, are shown in Table 4. These results are much more significant and align with expectations that Scenario 4 would produce the most cooling, followed by Scenario 3. The policy goal of Scenario 3 produces cooling of ~0.1˚C for each climate scenario. However, the efficacy of Scenario 4 is highly dependent on the climate conditions, producing an average cooling of 0.5˚C for cool summer conditions, 0.4˚C for mild summer conditions and 0.3˚C for extreme summer conditions.

Scenario difference	Cool (˚C)	Mild (˚C)	Extreme (˚C)
Scenario 1 minus Scenario 2	0.0	0.0	0.0
Scenario 3 minus Scenario 2	–0.12	–0.10	–0.10
Scenario 4 minus Scenario 2	–0.51	–0.40	–0.31

Table 5 - The difference in average daily 2m temperature between WSUD scenarios for each of the climate conditions for the representative residential area.

Time series plots of the representative area average temperature for each WSUD scenario again reinforce the observation that Scenario 4 is more effective during cooler summer days than during more extreme summer days (Figure 10). As stated earlier, the difference in temperature between the four WSUD scenarios increases when averaging over the representative residential area, compared to the whole domain, because the WSUD is more concentrated in the residential area and so the effects are more significant. The average difference in temperature between the WSUD scenarios is largest during the day (Figure 10), reaching more than 1˚C showing that the daily average reduction in temperature in Table 5 does not represent the diurnal effects of cooling. Our modelling suggests that the WSUD is less effective at night (Figure 10). We discuss the implications of this for human thermal comfort in the next section.

3.5 Human Thermal Comfort

The TARGET model is able to output the Universal Thermal Climate Index (UTCI), a measure of how warm a person feels, accounting for temperature, wind speed, relative humidity and radiation through the mean radiant temperature. Using the UTCI gives further insight into how WSUD changes the environment for humans. For example, the temperature may be reduced due to irrigated grass but people may not feel the difference due to the added humidity, which can make an environment feel warmer to a person.

The average difference in UTCI between WSUD Scenarios 1, 3, 4 and Scenario 2 for the three climate conditions is shown in Table 6. The reduction in UTCI is greater than the reduction in 2m air temperature in Table 5. These results indicate that incorporating WSUD into the landscape such as for Scenario 4 is highly beneficial for increasing the cooling effect 'felt' by humans. In terms of temperature, Scenario 4 cools by an average 0.51˚C during a cool summer day, but the UTCI shows that it 'feels' like cooling of 0.81˚C, meaning that WSUD is very effective at cooling the environment and improving human thermal comfort. Scenario 3 also produces significant UTCI cooling, with reductions of 0.22˚C during cool summer days. As with the air temperature, the efficacy of the cooling for UTCI is dependent on the climate scenario where the cool conditions have the most benefit and extreme conditions the least benefit.

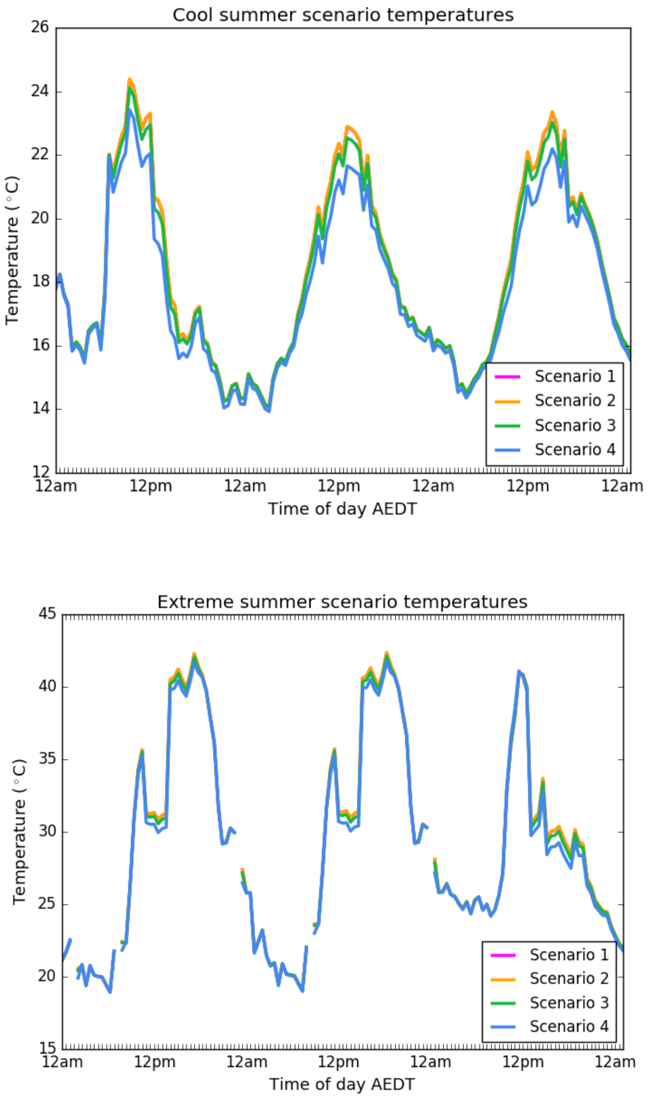


Figure 10 - The time series for the four WSUD Scenarios during the (a) cool scenario and (b) extreme scenario. Gaps are from missing data.

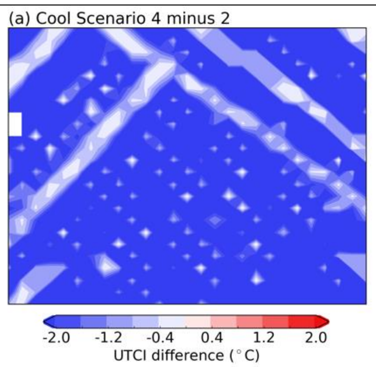
The difference in UTCI between Scenarios 1 and 2 suggest that Scenario 1 (no WSUD) is cooler than the control case of Scenario 2. This is counterintuitive since Scenario 1 would be expected to be warmer than Scenario 2. However, the differences between the land surface characteristics are very small (Table 2) where Scenario 2 is almost identical except for more water and much of this is away from the smaller residential area. As such, the small difference in UTCI between the two scenarios is not considered surprising.

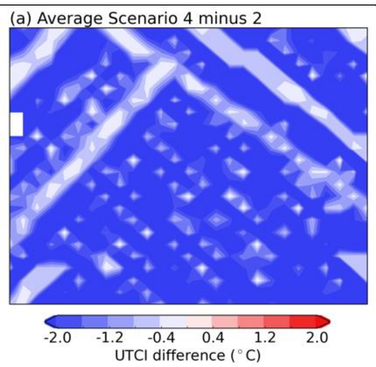
Scenario difference	Cool (˚C)	Mild (˚C)	Extreme (˚C)
Scenario 1 minus Scenario 2	–0.02	–0.01	–0.02
Scenario 3 minus Scenario 2	–0.22	–0.19	–0.14
Scenario 4 minus Scenario 2	–0.81	–0.68	–0.38

Table 6 - The difference in UTCI temperature between the WSUD Scenarios for each Climate Scenario for the small representative residential square

The aim of Scenario 4 was to produce 2˚C of cooling and it can be seen that this is achieved when considering the midday spatial patterns of UTCI difference across our representative residential area (Figure 11). The 2˚C of cooling is almost everywhere during the cool summer conditions and less pervasive in the mild and extreme conditions, but these results are still significant. A reduction in UTCI of 2˚C has the potential to save many lives during summer.

Cool Summer, Scenario 4 minus 2	Mild Summer, Scenario 4 minus 2	Extreme Summer, Scenario 4 minus 2





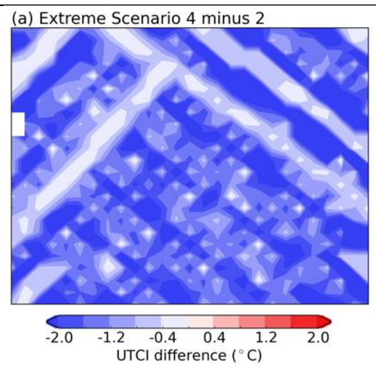
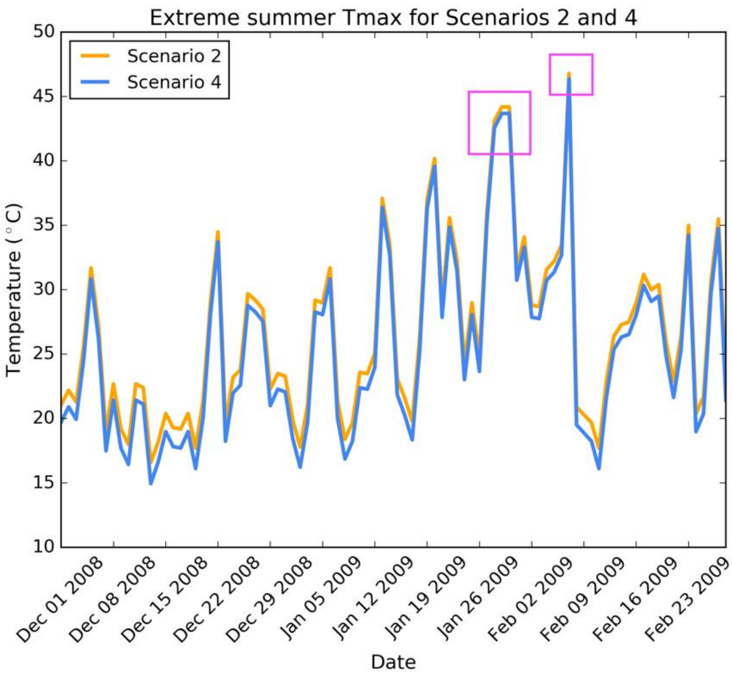


Figure 11 - The difference in UTCI between Scenario 4 and Scenario 2 at midday for the representative residential area for the cool, mild and extreme summer climate conditions.

3.6 Provision of Climate Data for Economic Analysis

To provide data for economic evaluation of the cooling provided by WSUD, the maximum and minimum temperatures from cool, mild and extreme summer conditions were reconstructed based on the modelling results from the four WSUD scenarios and three scenarios of climate condition. First, average summer temperatures (Dec – Feb) for Victoria were ranked from 1910–2017 and typical cool (1986–87), mild (1971–1972) and extreme (2008–2009) summers were identified. Maximum and minimum temperature data from Melbourne Airport weather station were then obtained for all 90 days (91 days for 1971-1972) for the three summers. The aim was to recreate the temperature during these summers if WSUD was present at the time, i.e. map the temperatures for the cases of Scenarios 1, 3 and 4, where Scenario 2 is used as the baseline for comparison observations. This was achieved by selecting the maximum and minimum temperature for each WSUD scenario from the middle day of the cool, mild and extreme three-day summer described above. Using this dataset, a linear interpolation was performed to create an algorithm whereby data input to the algorithm determines much cooling each WSUD scenario produces in each climate scenario. For example, data fed into the algorithm will produce a larger reduction in temperature for cool days than extremely hot days, because according to the modelling here, WSUD is more effective during cool summer days than hot summer days. Hence December 1 2008 had a cool maximum temperature of 21.1˚C, but if WSUD Scenario 4 was implemented the algorithm calculates a temperature of 19.7˚C, a difference of 1.4˚C. Furthermore, February 27 2009 had a temperature of 35.5˚C, but if WSUD Scenario 4 was implemented, the algorithm calculates a temperature of 34.8˚C, a difference of 0.7˚C.

The maximum and minimum temperature from the typical cool (1986–87), mild (1971–1972) and extreme summers (2008–2009) were input to the algorithm and the output data used to conduct the economic analysis. Figure 12a is a plot of this output for the 2008–2009 summer, comparing the 2m maximum air temperatures for Scenario 2 (equivalent to observations) with temperatures if there had been WSUD Scenario 4 present. The two purple boxes indicate the January 28–30 2009 heatwave and the February 7 2009 Black Saturday event. Figure 12b shows similar output for the minimum (overnight) 2m air temperature, where the differences between the scenarios are small.



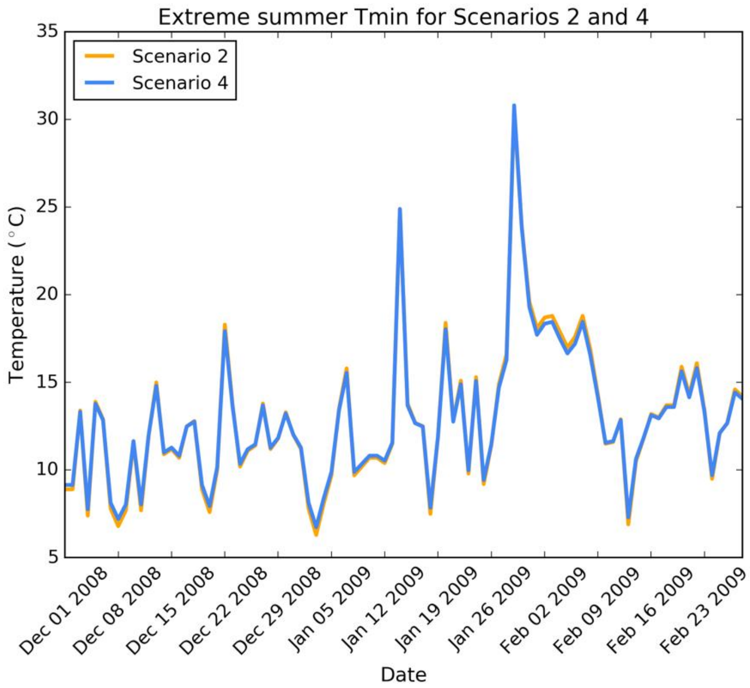


Figure 12 - Observational (Scenario 2) and the WSUD Scenario 4 2m air temperatures obtained by linear interpolation for (a) the maximum and (b) the minimum temperatures for the 2008-2009 summer. The two purple boxes indicate the January 28–30 2009 heatwave and the February 7 2009 Black Saturday event.

4. Concluding Comments

This report has documented work undertaken to assess the impact of different potential policy settings on the biophysical environment, including urban warmth, of a hypothetical suburban landscape in Melbourne. The cooling produced through microclimate modelling has been assessed in terms of its economic benefit in a partner report "Estimating the economic benefits of urban heat island mitigation – economic analysis", where the effects of heat reduction on mortality, morbidity, work productivity, electricity costs, along with an assessment of willingness to pay have been evaluated. This report clearly shows that the hypothetical Scenario 4 produces the greatest thermal benefits; this is a result of two key measures, a) maximising irrigation to a larger pervious surface fraction, and b) increasing the tree shaded area. It can be concluded that, even if Scenario 4 is not able to be achieved, the broad aim in terms of planning and design should be to increase the irrigated pervious surface area and level of shading in a precinct as much as is possible.

Appendix A

A1 Tree Canopy Size Assumptions

Increasing tree canopy cover is a common solution to achieve urban cooling objectives. The size and foliage density of a mature tree canopy in an urban setting is dependent on a complex interaction of factors, including tree species, soil moisture and drainage properties. Two factors known to potentially limit canopy growth are the soil volume available for plant root ball, and the water available through passive or active irrigation (especially if the tree is prohibited from accessing deep groundwater sources, such as in the early stages of growth). Assuming advanced tree stock is used on initial planting, a reasonable maturity might be achieved in 10-20 years.

The largest benefit to the ultimate canopy of a tree in an urban setting (streetscape) is to provide the tree with an optimal soil volume. As a rule of thumb, soil volume (m^3) should be at least approximately 33% of the ultimate desired canopy (m^2) (Figure A1). This relationship provides the minimum soil volume required for healthy growth to a well irrigated tree. For trees that receive less than optimal water, the soil volume will need to be larger to support healthy growth.

Providing optimal soil moisture and oxygen conditions to this minimum soil volume becomes the next objective to maximise canopy. A tree canopy area of up to 11% of the passive irrigation catchment will have optimal soil moisture conditions. However, the target canopy area should not be limited by the available catchment for passive irrigation. Rather, the soil volume provided should be determined from the desired canopy cover, even if the optimal catchment is not available. The growth of tree canopy can then be aided by manual watering and access to deep soil moisture as the tree matures.

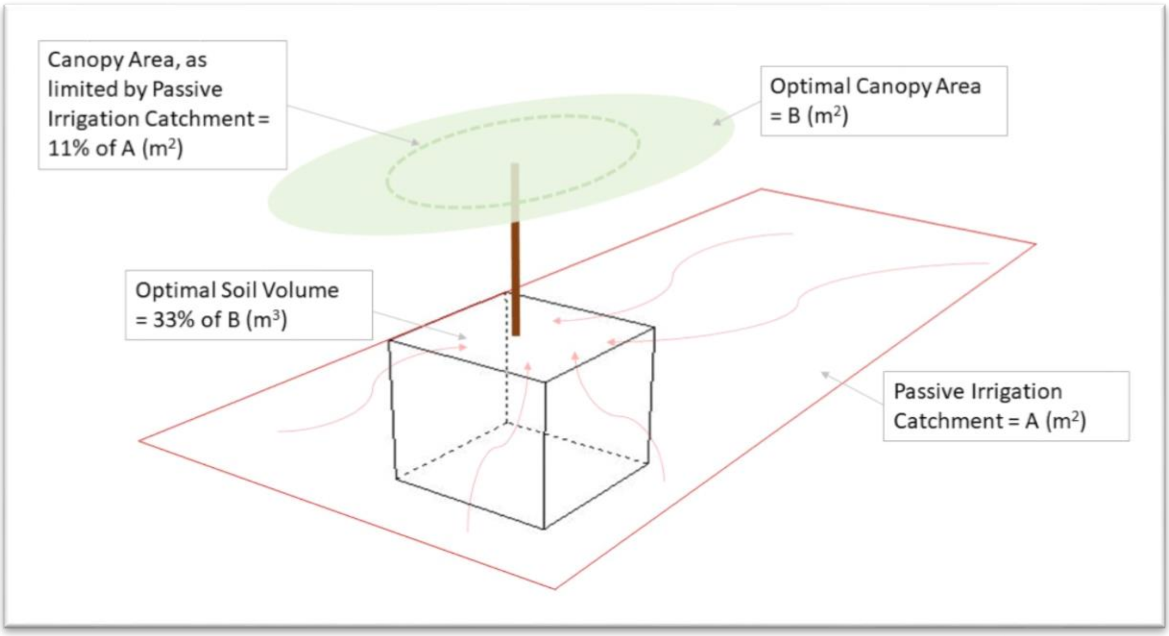


Figure A1 – Tree canopy and soil volume configurations

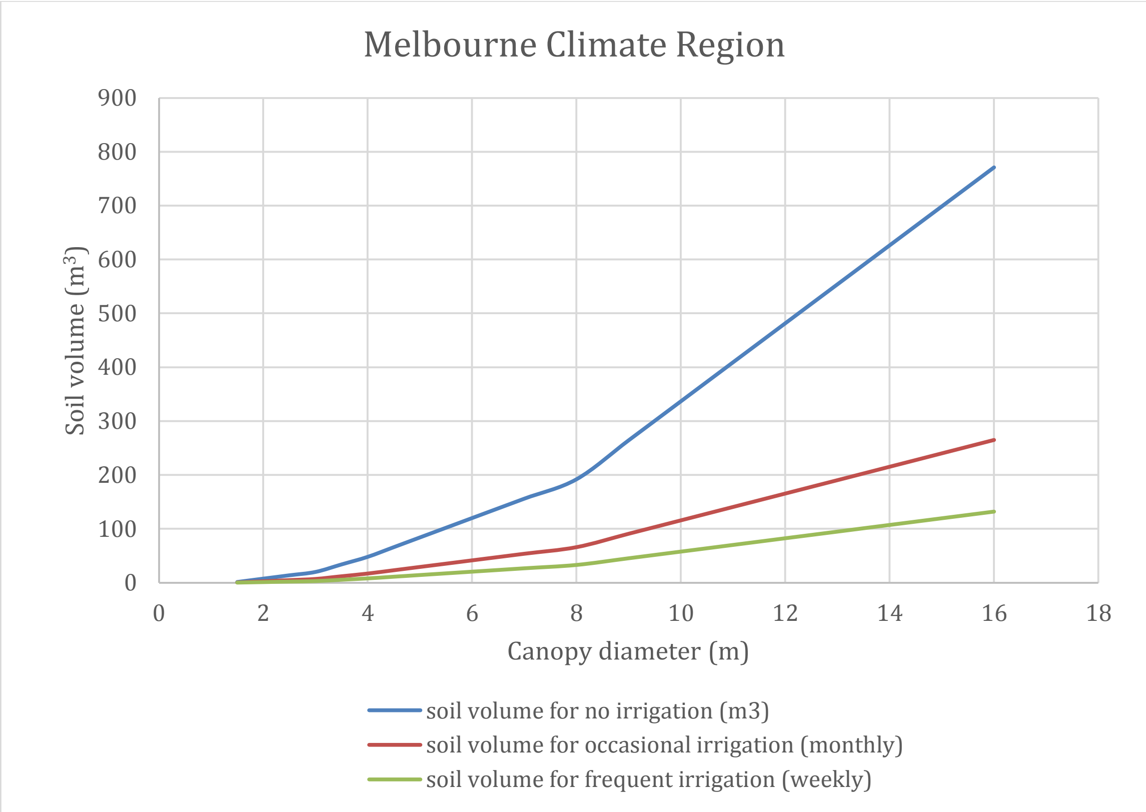


Figure A2 shows a relationship between soil volume and canopy area for three levels of irrigation: none, passive irrigation and manual, optimal irrigation.

The assumed street typology (Figure A3) allows a 3.4m median strip in lot frontage as shown in the figure below. Given an average 15m lot width, gives a potential soil volume (assuming a 1m depth) of 3.4 x 10m (allowing for driveways, services etc) = 34 m^2.

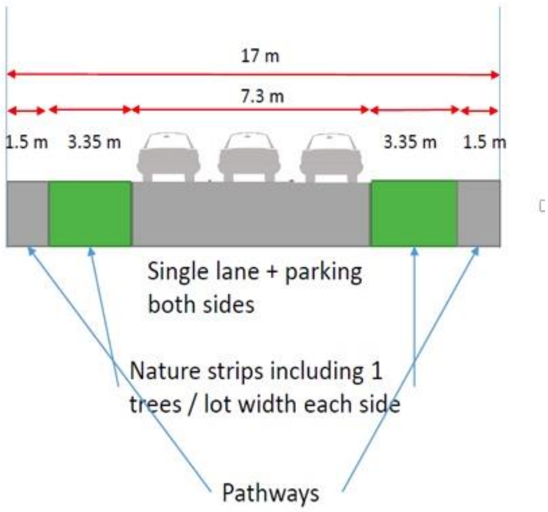


Figure A3 – Assumed street typology

For the purposes of this study, the following has been assumed:

- One tree per lot on residential streets has been assumed for Scenarios 1, 2 and 3, as per a local council tree planting policy and urban forest strategy.
- For all scenarios, it is assumed that 34 m^3 soil volume is available to trees as discussed above,
- For Scenarios 1 and 2, it is assumed that no additional irrigation of trees takes place, giving a tree canopy diameter of 3.5 m from the graph above, and a canopy area of **9.6 m^2**.
- For Scenario 3, passive irrigation is assumed from the road catchment. The catchment area is 15m x 7.3/2 m half road width = 56 m^2. Although this is a relatively small catchment, it will increase the water to the tree significantly. From the relationship above for infrequently irrigated trees, for the same soil volume the likely increased canopy diameter is 5.4 m, with canopy area of **22.8 m^2**.
- If we assume the passive irrigation gives frequent watering, the canopy diameter may be derived from the frequently watered curve, giving 8 m diameter and canopy area of **50.3 m^2**.

These are the canopy areas that have been used in the microclimate modelling for scenarios.

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