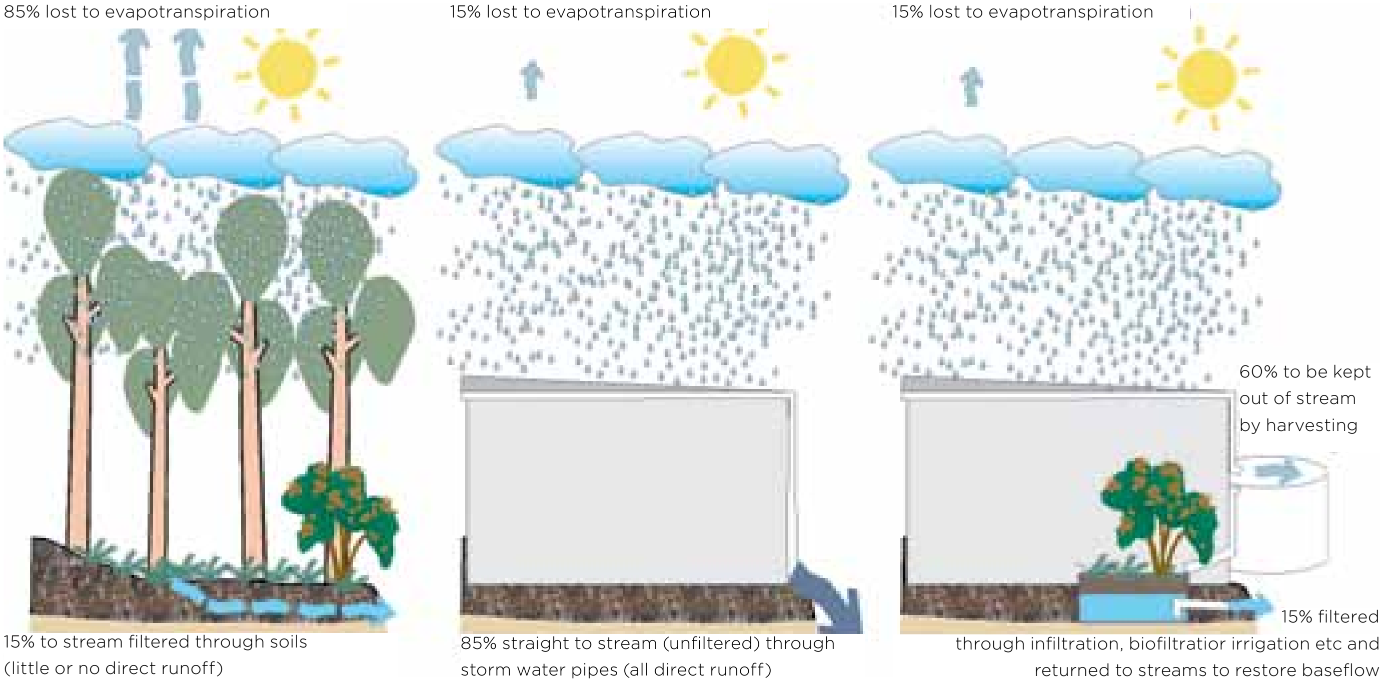

1 Changes to the Water Balance Resulting From Urban Impervious Surfaces

New Urban Storm Water Management Approaches

Using the Water Generated by Cities for Ecosystem Services

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Images as credited

Two major challenges facing humanity today are increasing water scarcity for a growing human population and the degradation of freshwater and coastal ecosystems resulting from water extraction and human land use (Vörösmarty et al. 2010). While these challenges are commonly portrayed as competing threats, for which trade-offs and difficult choices are necessary, cities of the world provide great opportunities for providing water for human use, adapting to climate change, and at the same time protecting and restoring receiving aquatic ecosystems.

Solutions that provide such benefits for the human inhabitants and aquatic ecosystems of cities are possible because of the unique nature of urban hydrology. The replacement of vegetated, pervious land with the roofs and roads that characterise urban settlements results in large increases in runoff volume. Water that once would have returned to the air as cool updrafts from moist soil and the plants of the forest is now delivered efficiently to streams through storm water drains, taking with it water that once infiltrated the soils and subsequently groundwater to slowly provide clean dry-weather flows in streams.

This runoff from impervious areas (roofs and paved land) is termed urban storm water. (Runoff from compacted pervious areas, such as lawns, can make a relatively small contribution to flows in storm water drains, but only during infrequent, high-intensity rainfall events.) Conventional approaches to the management of urban storm water runoff, which focus on rapid drainage of all runoff from urban areas, have resulted in the degradation of streams, rivers, estuaries, and coastal waters globally (Burns et al. 2012).

The provision of flow regimes that might allow rivers to sustain greater biodiversity and more natural ecological processes requires: the retention of urban storm water runoff in the catchment; the prevention of a large proportion from reaching receiving waters at all; and the filtration and slow release of a small proportion to mimic natural baseflow processes. The dispersed retention of storm water in urban catchments enables the provision of an additional water source for human use as well as other benefits, such as opportunities to reduce local temperatures associated with extreme heat events.

As part of a large research programme investigating the potential of urban storm water runoff as a water resource (Wong et al. 2012), we are studying the benefits of retaining and harvesting urban storm water in urban landscapes. In this article, we summarise our conceptual framework and preliminary research findings on the potential benefits of storm water harvesting and retention to the receiving water ecosystems and to the microclimate of cities.

Urban development projects (demonstration sites) are used by the "Cities as Water Supply Catchments Program" to establish proof-of-concept for new research insights and outcomes. New storm water management approaches to improve the health of creeks and rivers in established urban areas are being applied in "The Little Stringybark Creek Project" in Melbourne, Australia (www.urbanstreams.unimelb.edu.au). The project team is working with the local government, water authorities, and residents to test the design and implementation of a range of distributed storm water management practices delivered through a market-based funding instrument (See Fletcher et al. 2011, for a description of our initial programme of funding works through a market-based instrument). Officer, a new development in the south-east of Melbourne, Australia, seeks to establish new benchmarks in sustainability and liveability that can be replicated in urban growth areas by: (i) providing high-quality open spaces to support higher-density (outer-urban) development; (ii) reducing potable water demand by up to 70 percent; and (iii) reducing carbon emissions by up to 50 percent. In this article, we demonstrate the application of research insights into the master design and implementation of these two demonstration sites.

1. Typical changes in water balance from conventional drained impervious surfaces (left and middle), resulting in a large excess volume going to waterways. Storm water harvesting, combined with filtration, infiltration, and irrigation, can reduce runoff volumes to pre-development levels while helping to restore baseflows and return natural soil moisture to urban landscapes (right) (Image: Centre for Water Sensitive Cities).

2

Protecting Receiving Waters Through Storm Water Retention and Harvesting

Hydrology is a primary driver of the geomorphic and ecological condition of streams and rivers (Poff et al. 1997). Streams with even a small amount of conventionally drained urbanised catchment are invariably degraded with lost biodiversity (Walsh et al. 2005; King et al. 2010).

Given the underpinning nature of hydrology, we posit that storm water harvesting and treatment systems need to be designed to deliver flow regimes similar to pre-urban land to achieve healthy receiving waters. We developed four quantitative objectives to base the design of harvesting and retention systems on, we developed: (i) the frequency of untreated overflow from systems released to the stream; (ii) the volume and rate of filtered flow; (iii) the quality of filtered flow (based on concentrations of suspended solids, phosphorus, and nitrogen); and (iv) the volume of runoff prevented from reaching the stream. In each case an index quantified the degree to which each of these objectives approached the pre-urban condition. The performance of a system was determined as the mean of the four sub-indices.

We are currently trialing these indices as the basis for funding storm water retention works in the catchment of Little Stringybark Creek, with the ultimate aim of restoring the ecological condition of this degraded urban creek through in-catchment storm water retention. We hypothesise that the dispersed application of retention works designed to these flow-regime and water quality objectives should return ecologically important components of the flow regime, such as flow-pulse frequency, time exceeding mean flow, and baseflow index to values approaching reference forested streams (for example, see Clausen and Biggs 1997; Olden and Poff 2003; Booth 2005).

In turn, we hypothesise that such hydrologic (and associated water quality) restoration will result in a range of ecological indicators that we have been monitoring for a decade approaching those of reference streams.

To test the hypothesis that the ecological function and biodiversity of urban streams can be restored through storm water harvesting and better storm water management, we are retrofitting 200 hectares of suburban Mount Evelyn to restore Little Stringybark Creek and monitor the hydrological, water quality, and ecological responses of the creek and its tributaries. To date we have installed approximately 200 rainwater tanks and 90 raingarden or infiltration systems, across close to 170 properties (of a total of 750 in the catchment), and have a works programme in place to triple this level of retention in 12 months.

Meeting these objectives requires a combination of storm water harvesting, to reduce the volume of storm water and associated pollutants reaching the stream, and infiltration-based techniques, to provide filtered flows of appropriate quality, timing, and magnitude to protect receiving waters. As the excess water caused by impervious areas is a major challenge, the combination of such a suite of technologies is most likely to be needed.

2. In the Little Stringybark Creek Project, a biofiltration system (rain garden) treats all runoff from a residence and its paving (Photo: Darren Bos).

3. One of several large biofiltration systems in the Little Stringybark Creek Project treating runoff from roads and buildings throughout the catchment (Photo: Darren Bos).

4. Rainwater tanks used in the Little Stringybark Creek Project ranged from 2,000-litre tanks, for internal use and garden watering, such as this one on a residential property, to one-million-litre tanks, taking runoff from school buildings to irrigate sporting grounds (Photo: Darren Bos).

The dispersed retention of storm water in urban catchments enables the provision of an additional water source for human use as well as other benefits, such as opportunities to reduce local temperatures associated with extreme heat events.

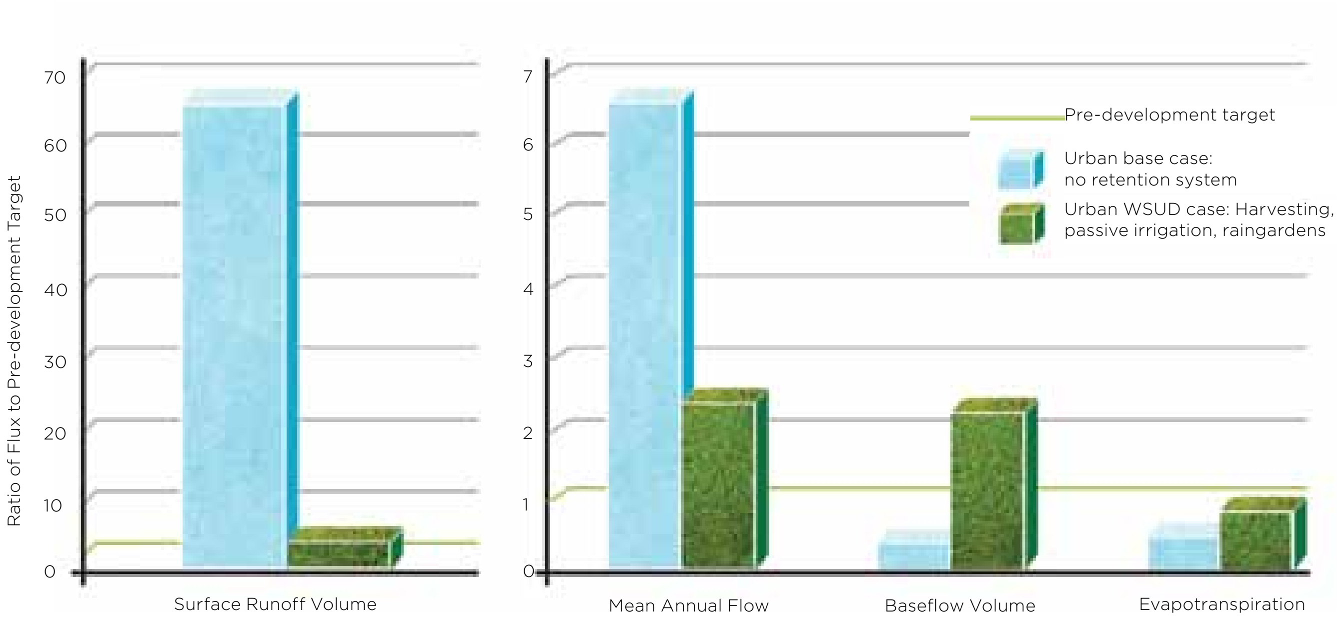
Providing filtered flows to mimic pre-urban dry-weather flows is a critical element of storm water management for flow-regimes (Burns et al. 2012). The drainage of impervious runoff through conventional drainage systems directly to receiving waters reduces the natural baseflow processes, as water is prevented from infiltrating soils and is delivered to streams only during rainfall. In some circumstances, this may be counteracted by anthropogenic inputs, such as leakages of water supply or sewage infrastructure (Price 2011). In cities such as Perth, Australia, and in some parts of the US, where discharge of urban runoff into groundwater is common because of highly permeable soils, increased baseflows are observed. The appropriate combination of storm water harvesting and infiltration techniques is thus required to ensure the appropriate pattern and volume of filtered flows.

The variation in baseflow responses to urbanisation (Price 2011) shows the importance of basing storm water management objectives on the local catchment context. Irrigation can be effective because it can be distributed over a wide area at low cost, increasing both evapotranspiration and infiltration. Combined with cheap, simple raingarden (vegetated) infiltration systems, such a distributed approach will help to provide other benefits, as well as restore catchment-scale hydrology, by distributing moisture throughout urban soils. However, the impact of dispersed local-scale infiltration on streamflow regimes remains an area requiring further research, so that systems can be sized to achieve near-natural baseflows (Hamel et al. 2012).

At Officer, an assessment of in-stream ecological responses to different urban development approaches predicted that conventional urban development (meeting current environmental protection requirements) within the catchment would likely result in the severe degradation or loss of in-stream ecological values. Riparian “sponges” (*Melaleuca* forests with deep soils for water storage) are being investigated at this demonstration site to manage the quantity, frequency, and quality of urban storm water runoff, thereby improving the ecological health of the urban waterway. The riparian sponge concept, developed through the master planning and design process, seeks to: (i) emulate natural flow processes, with almost all flows arriving the creek through sub-surface means; and (ii) emulate natural filtration processes, through the dense vegetation of the sponge.

A 100-metre-wide riparian corridor along the main waterway within the Officer development (required by legislation to provide habitat for the growling grass frog, a nationally vulnerable species) provided the opportunity for ecological sponges representing five to six percent of the contributing catchment (assuming no storm water harvesting) to be located within the riparian corridor. This meant that the riparian sponges did not impact the developable land; however, integrating some storm water management practices within the development may provide greater environmental, social, and economic benefits, such as improved ecological connectivity, microclimate, and amenity.

The need to store and use large volumes of water for the restoration or protection of flow regimes provides a substantial water resource that allows reduced demand on other water resources, such as potentially damaging extraction from riverine and groundwater ecosystems, or energy-intensive desalination of seawater. In addition, the dispersed nature of storm water retention systems required to achieve flow regime objectives provides new opportunities to improve the liveability of cities, for example, by supporting increased urban vegetation to reduce local temperatures during extreme heat events.



5 Measuring the Benefits of Storm Water Retention on the Urban Water Cycle

Reducing Heat Exposure in Urban Areas

The response of urban populations to their climatic environment depends on a combination of the population's vulnerability, climatic exposure, and ability to adapt. The responses to extreme heat commonly target managing highly vulnerable populations and encouraging adaptation.

Reducing exposure to stressful thermal environments in urban areas involves urban planning and design approaches that are sensitive to a changing climate. Dispersed storm water retention presents an opportunity (amongst other approaches) to create more thermally comfortable urban environments.

Current research undertaken by the Cities as Water Supply Catchments Program is quantifying the changes in temperature and human thermal comfort (HTC) associated with combinations of various storm water retention technologies. This work is revealing the substantial capacity of these technologies to cool the urban environment, particularly during the day, and to improve HTC, and is helping to prioritise their implementation.

Our preliminary research results are reinforcing the benefits of street trees in improving HTC at the street scale during the day through modest reductions in air temperature and significant reductions in the mean radiant temperatures (a measure of the influence of radiative energy on the body) from tree canopy shading. Urban street tree monitoring in Bourke Street, Melbourne, has shown that during spring (October 2011), on average, mean radiant temperatures were up to 18 degrees Celcius lower at midday under tree canopy shade. Further, our monitoring of experimental and installed green roofs has shown that they markedly lower surface temperatures compared to traditional roof types, with a consequent reduction in air temperatures in the near vicinity. These thermal benefits are maximised at warmer times of the year.

5. Modelling showed that fluxes could be returned to near their pre-development levels for low-, medium- and high-density developments, using application at a wide range of scales (Image: Centre for Water Sensitive Cities).

Fit-for-place urban design should maximise the thermal benefits of storm water retention technologies. Our recent research has highlighted the large micro-scale variability of climate across neighbourhoods. The airborne thermal imagery collected during our summer 2011 field campaign at Mawson Lakes, Adelaide, reveals large variations in surface temperatures across relatively small distances with clear temperature contrasts between built and natural surfaces, highlighting the need for distributed technologies throughout the landscape for more effective neighbourhood cooling. Integrating storm water retention and harvesting systems into the landscape can greatly assist in reducing surface temperatures.

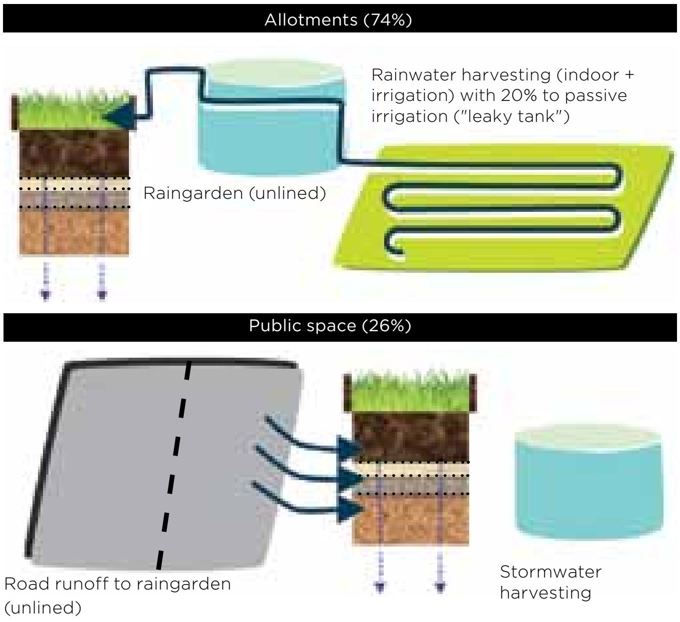
Preliminary analysis of air temperatures during the Mawson Lakes campaign has reinforced the notion that denser urban environments are warmer at night and should be prioritised for the implementation of storm water retention systems, particularly for areas where people congregate. Air temperatures across the neighbourhood varied by up to eight degrees Celsius at times, with the maximum differences occurring near sunrise.

There is ongoing research to further quantify the benefits of storm water retention and harvesting on urban climates at a range of scales. Drivers of temperature at the micro scale are complex and it is often difficult to disentangle specific contributing factors in observational studies. Urban climate models at a range of scales are a useful tool for scenario modelling and help in understanding dominant microclimate drivers. There is limited modelling capacity at the micro-scale: an issue that we are currently addressing. However urban climate-modelling capacity is more advanced at the local- to city-scale, as is the capacity for modelling the effects of storm water retention on climate. However accurately parameterising urban land surface schemes in climate models is a challenge and further refinements are necessary. Observational studies can help in parameterising and validating models. We have two local- to city-scale modelling projects underway to assess and prioritise the effectiveness of storm water retention technologies.

In the meantime a strong indication of the effectiveness of water in cooling the environment is provided by our observational work using thunderstorms as analogues for landscape irrigation. In the Melbourne region, for rural landscapes of less-than-10-percent imperviousness we observe a characteristic surface temperature cooling of 0.6 degrees Celsius for every millimetre of rainfall delivered, while landscapes of more-than-10-percent imperviousness show about only half as much surface temperature cooling. These results were from a discrete thunderstorm event and in ongoing work we are seeking to generalise these results.

The priority areas to target for storm water retention remain those locations of high population vulnerability, denser urban environments, with little or no vegetation and that are areas of high heat exposure, areas with older and less efficient housing stock, and areas of high human activity.

Our initial findings suggest that some storm water management technologies may be more effective at cooling and providing HTC benefits at different times of the day. The design and implementation of storm water retention and harvesting approaches for the intention of modifying urban climates will need to respond to specific location and time requirements (for example, targeting an outdoor event during the day).



6 Techniques for Restoring the Urban Water Balance

6. Example of the combination of storm water harvesting and storm water retention systems to restore urban water fluxes for a typical medium-density development (allotments and public space represent 74 percent and 26 percent of the area respectively) (Image: Centre for Water Sensitive Cities).

7. Remnant swampy *Melaleuca* forest, similar in form to the riparian sponges planned for Officer (Photo: Geoff Vietz).

8. The thermal image depicts high variability in surface radiometric temperatures across different land use types (Image: Centre for Water Sensitive Cities).

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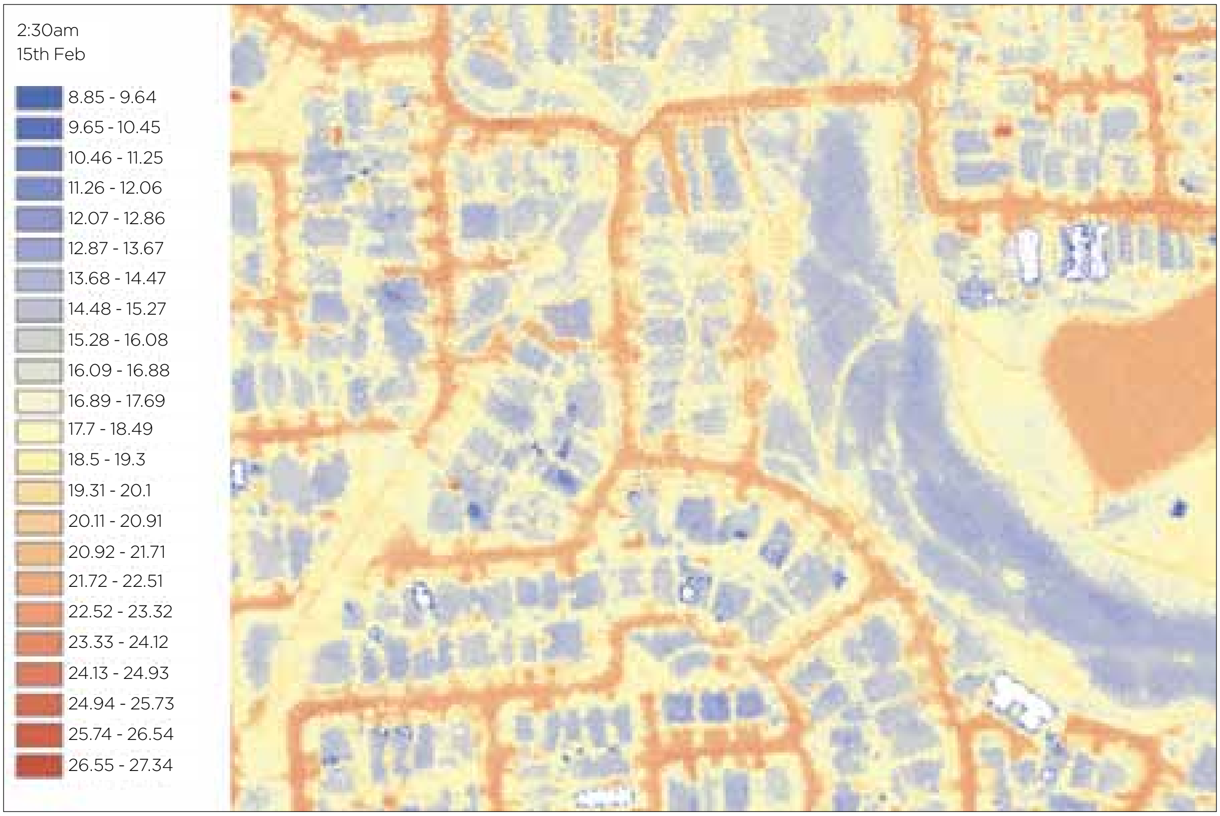
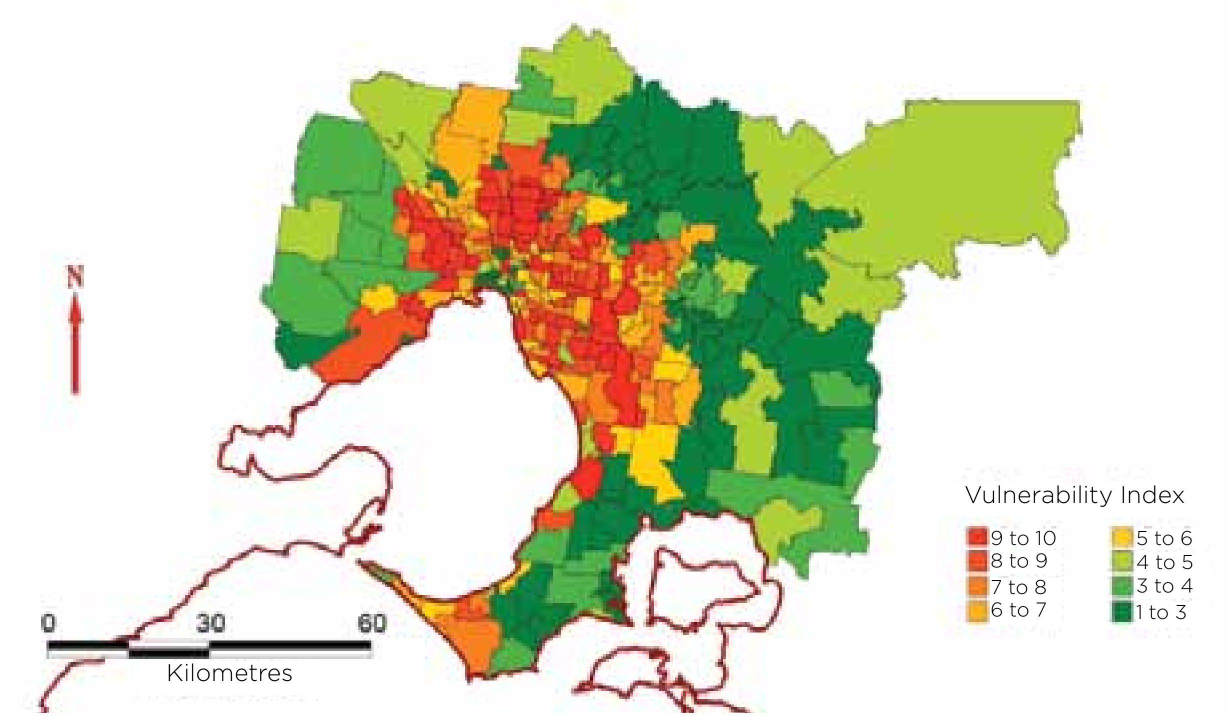


8 Uncorrected Airborne Thermal Image From Mawson Lakes at 2:30 a.m.



9 Heat Vulnerability Index Map of Melbourne by Postcode Area

Human Health and Thermal Comfort

The risks of extreme summertime heat for urban populations can be reduced by: (i) using climate- and health-based approaches, such as threshold temperatures to predict health-threatening heatwaves, mapping population vulnerability, and urban heat islands during heat events; and (ii) identifying the thermally comfortable temperature ranges for Australian populations, by measuring HTC in outdoor urban areas. Urban heat mitigation strategies can then be directed towards developing urban areas that are thermally comfortable for the local population.

At the city scale, measuring population vulnerability to extreme heat events using an index of risk based on social, health, and environmental factors enables the identification of "hotspots" and development of targeted mitigation strategies that are both population- and place-specific (Loughnan et al. 2009).

Our group is currently finalising a report to the National Climate Change Adaptation Research Facility (NCCARF) that establishes heat-mortality thresholds and heat vulnerability maps for all Australian capital cities. Temperature thresholds are specific temperatures above which mortality or morbidity increases. Even small reductions in temperature, such as those associated with water retained in the landscape, can save lives (Nicholls et al. 2007). Our NCCARF work on heat and mortality also extends to the predicted impacts of climate change. Furthermore, in Australia, like much of the world, heatwaves are predicted to increase in frequency, duration, and intensity in the coming decades. Increases in the number of "hot" days above current mortality-heat thresholds are also expected. Between the present and 2040, under a moderate emissions scenario, the number of days exceeding the maximum temperature thresholds are predicted to: more than double in Melbourne, Brisbane, and Adelaide; double in Hobart; and increase by approximate 30 to 50 percent in Sydney, Perth, and Darwin. This will likely impact population health significantly, unless adaptation occurs.

Designing outdoor environments that take advantage of air circulation, particularly downwind from water sources, and implementing green infrastructure as well as street orientation and tree planting to avoid the midday sun will provide cooler environments that are more comfortable during hot weather.

Changing Urban Water Management to Maximise Ecosystem Services

The combined work of our two groups has identified substantial potential synergies for the protection of urban aquatic ecosystems and the improvement of urban microclimates through the retention, harvesting, irrigation, and infiltration of urban storm water. While some technological challenges remain for the implementation of such systems and to maximise the multiple benefits of storm water retention, perhaps the biggest challenges to realising these benefits are social, economic, and political. A strength of the Cities as Water Supply Catchments Program is its integration of research projects that address all of these challenges.

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9. The index was developed from a range of risk factors that include age, health status, type of housing, and socio-economic status (Image: Loughnan et al., 2009).