centre for water sensitive cities
cities as water supply catchments

PROJECT 3:

Green Cities and Micro-Climate

Report:
Urban Climate Model Selection for Modelling WSUD Features

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Contents

1 Executive summary

Quantifying the positive impacts of introducing WSUD (water sensitive urban design) in urban areas on HTC (human thermal comfort) requires robust tools. Urban climate modelling approaches present an opportunity to study the many options and configurations of WSUD features of an urban area, to understand their influence on urban climates at a range of scales. Urban landscapes are extremely complex terrains to model given the range of building geometries, urban materials, street orientations, vegetation, surface types, and water features.

Project 3 of the Cities as Water Supply Catchments program aims to apply a modelling tool for the assessment of the urban climate impacts of WSUD, in particular temperature and human thermal comfort. In selection of appropriate modelling tools, an assessment of existing model approaches and modelling capabilities is required, along with a clear understanding of the scales over which modelling tools are applied.

Urban climate modelling techniques at a range of scales are evolving and capacity is growing in their ability to represent urban surfaces and test for a variety of scenarios of landscape design and implementation of WSUD and vegetation. To work efficiently and accurately, models are designed using a variety of strategies and techniques to fit best with the intended use and scale, and it is important that the most appropriate model is selected.

This report reviews a number of models and land surface schemes that are available across the urban climate modelling community. It outlines the current capacity of urban climate models and land surface schemes to represent vegetation and WSUD. In particular, it concentrates on the capacity to model evapotranspiration (latent energy fluxes), given this is often described as an important mechanism driving urban cooling. The report focuses on two scales:

- **Local-scale:** This scale is commonly of the order of around 1-2 km. This scale of model is most appropriate for understanding broad impacts of WSUD on temperature at the neighbourhood scale.
- **Micro-scale:** This scale is in commonly in the order of around 1-100 m. This scale of model is most appropriate for understanding more detailed impacts of WSUD on temperature and human thermal comfort and the street scale.

Local scale land surface schemes can be applied to the meso-scale (city-scale) using a grid or a 'tiled approach' to understand large scale urban effects such as the urban heat island. Urban land surface schemes and micro-climate models can also be coupled to atmospheric models, to model interactions between the land surface and the atmosphere. In order to accurately model and predict temperature gradients in urban environments, especially considering cooling effects of water and vegetation, models will need to capture the processes driving energy and water budgets of urban climates, and the interactions of the three layers of soil, plants, and atmosphere and the path water takes between them.

Local to meso-scaled (and global scaled) urban climate modelling is well established and mature. A number of models are available for urban climate research purposes (LUMPS/SUEWS, WRF, CCSM, JULES, and CABLE). A variety of strategies are used to model the urban canopy by these models, some of which are more suitable for modelling WSUD features within urban canyons. However, none of these models will be able to model WSUD features at a detailed street-level resolution. This makes them better tools for looking at overall broad impacts of WSUD techniques on moderating temperature extremes and best serving HTC as well as urban heat island (UHI) effects when applied at the city scale. **At this scale, LUMPS/SUEWS, which has the most complete water cycle features, appears to be a good avenue to model these features at this resolution.**

Micro-scaled modelling is far less mature and few options exist at this scale. Surveyed models include SOLWEIG, TUF-3D, MIMO, MITRAS, ENVI-met, and OpenFOAM. ENVI-met has revealed limitations which diminish its usefulness in assessing WSUD features at this time, though modelling development is ongoing. SOLWEIG could prove useful in examining WSUD impacts through changes to radiation and heat, but a lack of complete vegetation and water modelling limits its overall usefulness. Models based on computational fluid dynamics (CFD) such as MIMO, MITRAS, and OpenFOAM have great potential but are not freely available, would require a large effort to use, and intense computational power to realise their potential. **TUF-3D comes closest to meeting the criteria, but does not include full vegetation modelling, so is limited in its overall usefulness.**

In summary, this review highlights that no existing models explicitly include all forms of WSUD. The capacity to include WSUD is far more advanced for local-scale modelling, though limitations still exist, while at the micro-scale, significant model development is required.

2 Introduction

2.1 Climate change and urban heat island

Climate change is a pressing issue that requires understanding of its impact at many different levels. Uncertainly exists over what the exact impacts will be of a changing climate, especially within urban areas, and how that will impact the health of people. We need to provide data and predictions around these issues. In Australia, recent trends have seen increased warmer nights and decreased frost days (Alexander & Arblaster 2009), with sharp rises of these predicted in the future under Intergovernmental Panel on Climate Change (IPCC) B1, A1B, and A2 scenarios. More worrisome are predictions concerning increasing extremes, such as longer duration heat waves (Alexander & Arblaster 2009). Such extreme events are found to be of great significance in contributing to human mortality (Laschewski & Jendritzky 2002) especially after heat wave durations (as well as day and night average temperatures) exceed certain thresholds (Loughnan et al. 2010; Nicholls et al. 2008). Given these concerns over human health, mitigation and adaptation needs to be examined.

2.2 Increased urbanisation

Much attention has been devoted to studying the climate and changes at a global level and possible impacts of these changes (IPCC 2007), but much less at a micro-climate level, that at which people live. Patterns of human habitation are changing. Increased urbanisation rates in Australia (PDDESA 2007) are running in parallel with an increasingly ageing population (Commonwealth of Australia 2010) and the greater vulnerability to increasing temperature extremes that brings (Laschewski & Jendritzky 2002). One implication of increased urbanisation is urban heat island (UHI) effects, that is increased temperatures in urban areas due to a range of factors including night-time heat storage and decreased evapotranspiration (Coutts et al. 2007). These effects further exacerbate the changing climate trends towards longer heat wave durations and hotter nights. Housing trends in cities like Melbourne have been towards new detached dwellings in the outer suburbs with some gradual rebuild of medium and high density housing confined to the inner and middle suburbs. Market demand is also emphasising increasing the supply of low to medium density housing (DSE 2002). Cities such as Melbourne are becoming more populous, denser, and more spread out all at the same time. As urban areas are expanded and morphologies changed, micro-climates will impact those populations differently.

2.3 Adaptation/mitigation strategies

In order to protect human health in light of projected changes to climate and urban development trends, response strategies will be needed. Mitigation strategies include plans to reduce CO_2 emissions through increased public transport and greater energy efficiency (ClimateWorks 2010) as well as projects to increase CO_2 storage in vegetation and trees (City of Melbourne 2011). However, mitigation will not be enough. Changes to urban climates in the future will require adaptation to the expected increases in extremes.

Adaptations can take two forms, either measures to cool buildings and houses, or measures to try and cool the surrounding areas. The first is traditionally accomplished through the use of shading, ventilation, and insulation. Also, building interiors can be cooled artificially through refrigerated or evaporative air cooling systems. Looking outward, building materials suited to reflecting solar radiation can be used, as well redesigning arrangements of buildings in urban morphologies so that they benefit from cooling effects through their orientation to wind flow and solar shading (Taylor & Guthrie 2008). Finally, in an effort to cool surrounding areas, vegetation and water can be incorporated into the urban landscape, specifically for their cooling effects (Shaw et al. 2007).

2.4 Water sensitive urban design as mitigation and adaptation

Adaptation strategies that include principles such as those used in Water Sensitive Cities (Wong & Brown 2009) can be incorporated into an urban landscape. Water is captured and stored and reused instead of being expelled from the system as stormwater. Trees and other vegetation fulfil a number of ecosystem services such as nutrient/pollution filtration, shading, and cooling through evapotranspiration, in addition to the benefits of providing a more resilient water supply for the urban area. While these strategies act as adaptation strategies, using the cooling benefits of water to moderate temperatures in the urban environment, their benefits can also act as mitigation strategies. New urban development designed to encourage evapotranspiration and energy dispersal through latent energy fluxes, such as increased vegetation in open spaces and park lands or through green roofs and green walls can also act as a CO_2 sinks (Coutts et al. 2010). Cooling through increased albedos of urban surfaces and passive cooling techniques can decrease the amount of anthropogenic heat released in urban areas through air conditioners as well as a savings in CO_2 emissions due to reduced requirements for mechanical cooling (Coutts et al. 2010). Finally, increased use of urban stormwater run off has a number of mitigation benefits. Urban areas can secure their water supply and reduce reliance on centralised water systems, which can be energy and emission intensive. Filtration of nutrients and pollutants out of stormwater can take place without impacting catchment areas and oceans and without withdrawing water from rural areas (Coutts et al. 2010).

2.5 Modelling the benefits of Cities as Water Supply Catchments

The Cities as Water Supply Catchments project has a number of goals including relieving water shortages as well as increasing the health of urban waterways (Centre for Water Sensitive Cities 2011). In addition, making retained stormwater a permanent feature within urban areas, along with the vegetation associated with its use, can have important side effects on urban climates. A number of key questions about these side effects need to be answered through the use of modelling, quantifying possible benefits.

- What decreases in temperatures both spatially and temporally can be expected in an urban area?
- What benefits can be expected in moderating effects of heat waves and temperature extremes?
- What is the optimal arrangement of WSUD features within an urban landscape and what is best practice in their use for human thermal comfort?

This report will survey the available models (both at local/meso-scaled and micro-scaled) and assess their suitability to answer these questions. In order to accurately model and predict temperature gradients in urban environments, especially considering cooling effects of water and vegetation, models will need to capture the processes driving energy and water budgets of urban climates (section *3.1*) and the interactions of the three layers of soil, plants, and atmosphere and the path water takes between them (section *3.2*).

3 Fundamentals of urban climates

3.1 Urban energy and water budgets

There are many drivers that cause temporal and spatial variations in temperature across a micro-climate environment. Incoming solar radiation (shortwave radiation from the sun) is the main driver of the energy budget of a urban micro-climate. The surface radiation budget of an urban area is defined by Oke (1988) in Figure 1 and in equation (1):

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \qquad (1)$$

with Q^* being net radiation, balanced by terms for incoming (↓) and outgoing (↑) K (shortwave solar radiation) and L (longwave thermal radiation).

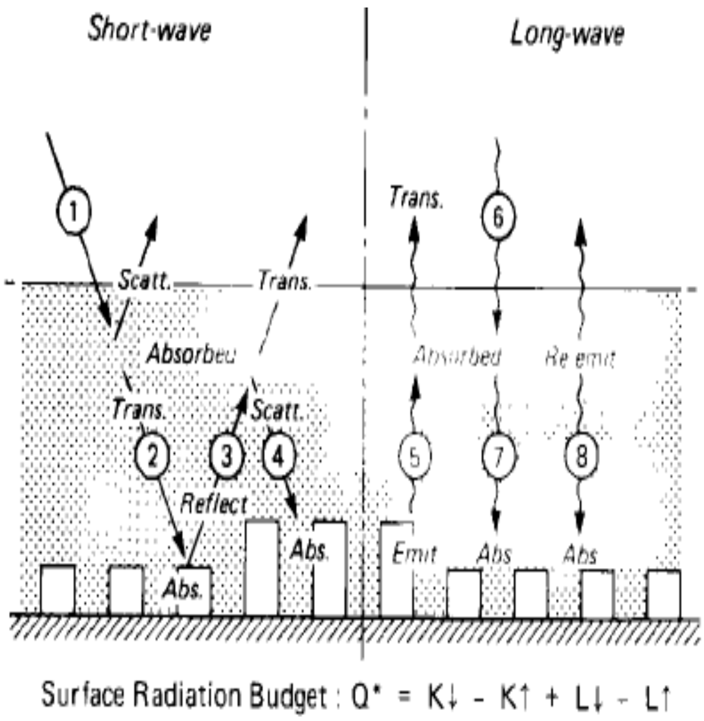

Figure 1: Urban surface radiation budget (Oke 1988, p. 473)

Incoming shortwave solar radiation can be scattered in the atmosphere, transmitted through and either absorbed by the surface or reflected back out. Reflected shortwave will be re-scattered or transmitted outward as well as absorbed and stored. Absorbed shortwave radiation accordingly will be re-radiated as longwave radiation, following possible paths of transmission outward or reabsorbed by the surface.

The surface energy budget, in more detail, within an urban environment is described by Oke (1988) in Figure 2 and in equation (2):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \qquad (2)$$

with Q^* being net radiation, Q_F anthropogenic heat, Q_H sensible heat flux (heated air), Q_E latent heat flux (through water evaporation), ΔQ_S heat storage (within the environment), and ΔQ_A net advective (horizontal air movement) heat flux.

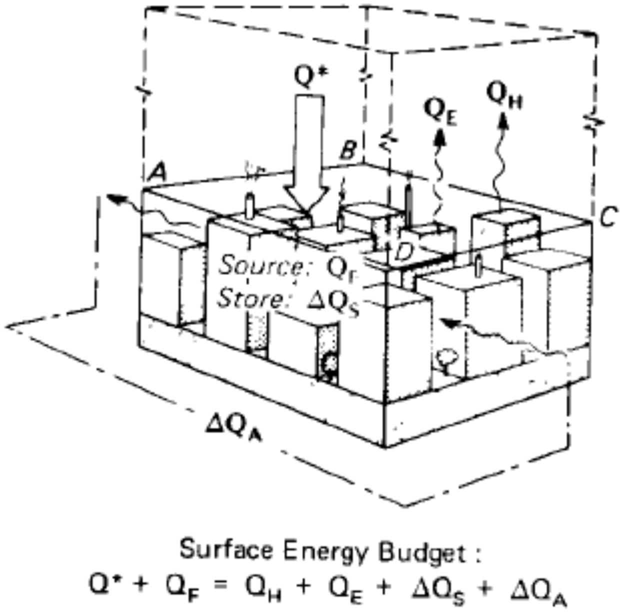

Figure 2: Urban surface energy budget (Oke 1988, p. 473)

The role water plays in an urban micro-climate can be described by the surface water budget, given by Oke (1988) in Figure 3 in equation (3):

$$p+F+I=E+\Delta r+\Delta S+\Delta A \qquad (3)$$

where p is precipitation, F is moisture release by combustion, I is the piped water supply, E is evapotranspiration, Δr is net run-off, ΔS is net moisture storage, and ΔA is net moisture advection. The evapotranspiration term (E) links together the energy and water budgets as water evaporation (latent energy) is an important cooling element in an environment.

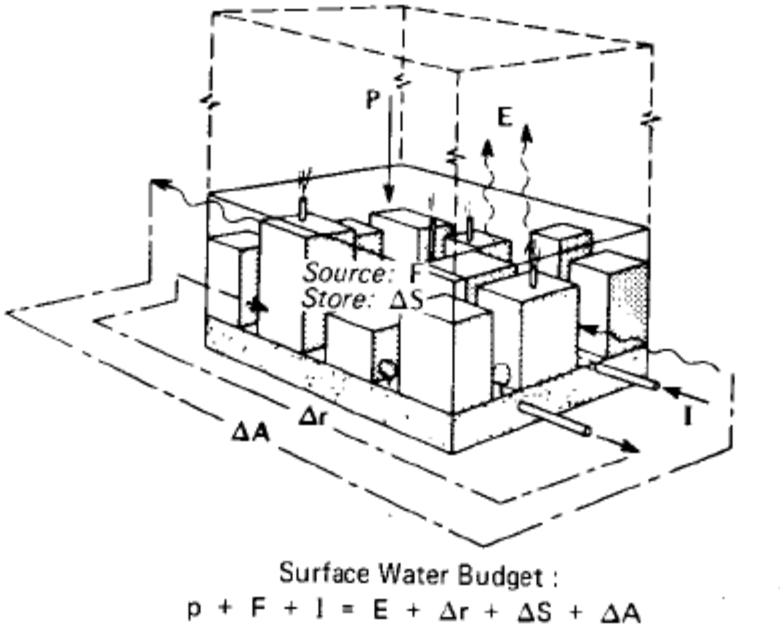

Figure 3: Urban surface water budget (Oke 1988, p. 473)

A final consideration in the drivers of an urban micro-climate is the role wind plays in temperature variations across an environment. Oke (1988) presents idealised representations of atmospheric boundary layers (Figure 4a) and the downwind effects created by features on the surface (Figure 4b). The urban canopy layer (UCL) extends from ground level to the top of urban buildings where these features create roughness with wind flow patterns and layer mixing. These effects extend upward through the urban boundary layer (UBL), finally leading to the planetary boundary layer (PBL), where effects are not seen. At a micro-climate level, wind provides mechanical mixing of atmospheric layers. Reduced wind speeds may have the effect of allowing warmer temperatures to build during a warm afternoon. On the other hand, a calm night will tend to support reduced temperatures more than one where wind mixes warmer air aloft with colder ground air (Ahrens 2004). Features within an urban micro-climate which either encourage or discourage wind and the mechanical mixing of warmer and cooler air layers will do much to create temperature variations across this area.

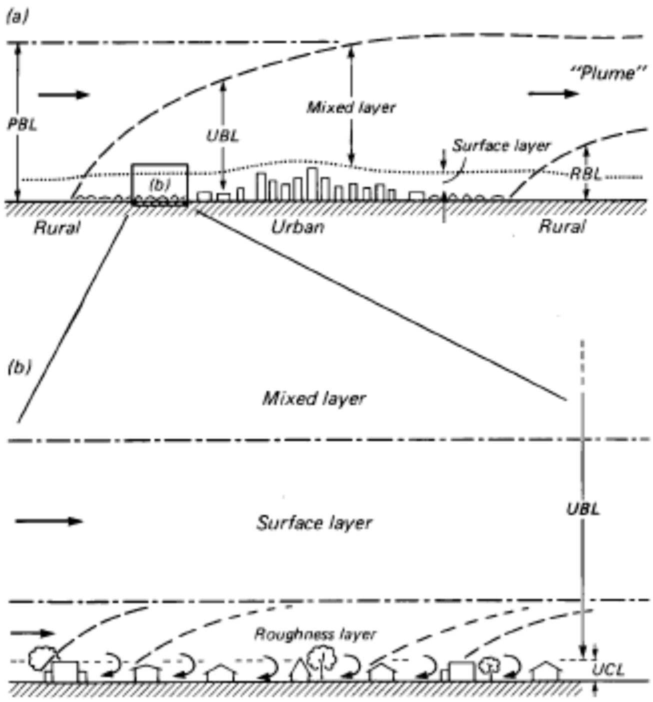

Figure 4: Boundary layer structures over a city Oke (1988, p. 473)

3.2 Soil/water, plant and atmosphere interactions

In modelling an urban environment, the interactions of water through soil and plants with the atmosphere have important implications on urban micro-climates. The water cycle, starting from the soil through plants to the atmosphere and back to the soil is a complex process. Philip (1966) describes it as the 'soil-plant-atmosphere-continuum'. Water flow between the three layers can be examined individually through different scientific disciplines. However, a complete understanding, as well as accounting for the energy flows associated with these transfers, requires that all the interactions must be considered as a whole.

Water stored in the soil through precipitation, irrigation, or sub-surface water movement is taken up by plants and stored in cells. Plant photosynthesis releases water, making water available for latent heat fluxes within urban canyons. Moisture release will peak during daytime while moisture uptake will peak during night-time hours. Highly water stressed vegetation can shut down or reduce photosynthesis until water becomes available again, meaning rates are subject to moisture availability in the soil.

A large number of variables influence the rates and timing of these water flows at each stage.

- Soil moisture can depend on water inputs and the soil's ability to store water.

- Different plants, with different root depths and different water needs, can take up water at different rates and at different soil depths, and release water at differing times and points of the urban canopy.
- Varying atmospheric conditions determine the eventual path of the water back in to the soil.

As a result, adding moisture to the soil does not necessarily lead to a linear relationship with evapotranspiration rates. Plant physiology and root reactions to wet and dry conditions, combined with varying climatic conditions introduces a hysteresis (phase difference) in these rates (Teuling 2007).

4 Modelling strategies and scales in relation to urban climates

In modelling urban climates, there are a number of different ways the areas can be modelled. To work efficiently and accurately, models are designed using a variety of strategies and techniques to fit best with the intended use and scale.

4.1 Modelling scales

4.1.1 Global scale

The most commonly known climate models are global scaled, used extensively in the IPCC assessments examining global climate change as well as by meteorological organisations for weather predictions. Global scale covers scales from 2000 km to the entire globe. These models are commonly atmospheric general circulation models (GCM) (section 4.2.2) modelling radiation, heat, water vapour and momentum fluxes across the land-surface atmosphere interface. A component of these models, land surface schemes (LSS) (section 4.2.4) are designed to calculate the temporal evolution of these fluxes, differentiating between bare ground and vegetation fluxes.

4.1.2 Meso and Local scale

To look at urban climates, higher resolution scales are needed (Figure 5). Meso-scale covers the range from 2000 km to 2 km, further subdivided into meso-α (200-2000 km), meso-β (20-200 km), and meso-γ (2-20 km) (Pielke 1984). Regional scaled modelling resolves at the meso-α range. Local scaled modelling, resolving at a city-wide level, sits within the meso-β and -γ scales. These models allow examination of rural and urban areas and how interactions with an urban canopy (buildings and other structures as well as urban trees) impacts climate conditions at these more local scales. These models are commonly scaled down global models, relying heavily on LSS (section 4.2.4) and urban components to calculate the interactions of these urban canopies.

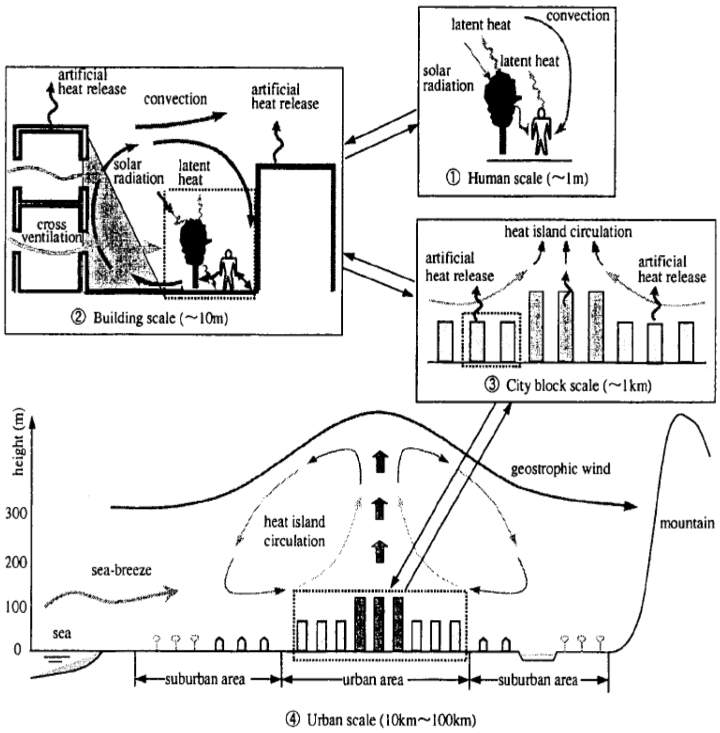

Figure 5: Various scales related to wind climate (Murakami et al. 1999, p. 58)

A variety of approaches are used to model urban areas, falling into twelve categories. These choose whether all fluxes are considered or not. If Q_F (anthropogenic heat) is considered, it can calculated or set to a reasonable constant (Figure 6-2). Q_E (latent heat flux) can also be considered or not, and either calculated or fixed. Vegetation can be considered and modelled as an integrated module or a separate tile (Figure 6-1). Vegetation modelling can be simplified into something that is merely an obstacle to sunlight and wind, or include all its processes of photosynthesis and water storage and transfer.

The geometry of the urban canyons can be addressed in a number of different approaches, with increasing levels of complexity and detail. Urban areas can be treated as a simple slab or with walls, roads, and intersections (Figure 6-4,5). These features can interact with fluxes (reflections, albedos, and heat storage) in single or multiple levels of interaction (Figure 6-6). With increasing levels of complexity, results are potentially more accurate and detailed, but at higher computational and input setup costs. Evaluation and experimentation must determine which approach is best for the intended modelling use.

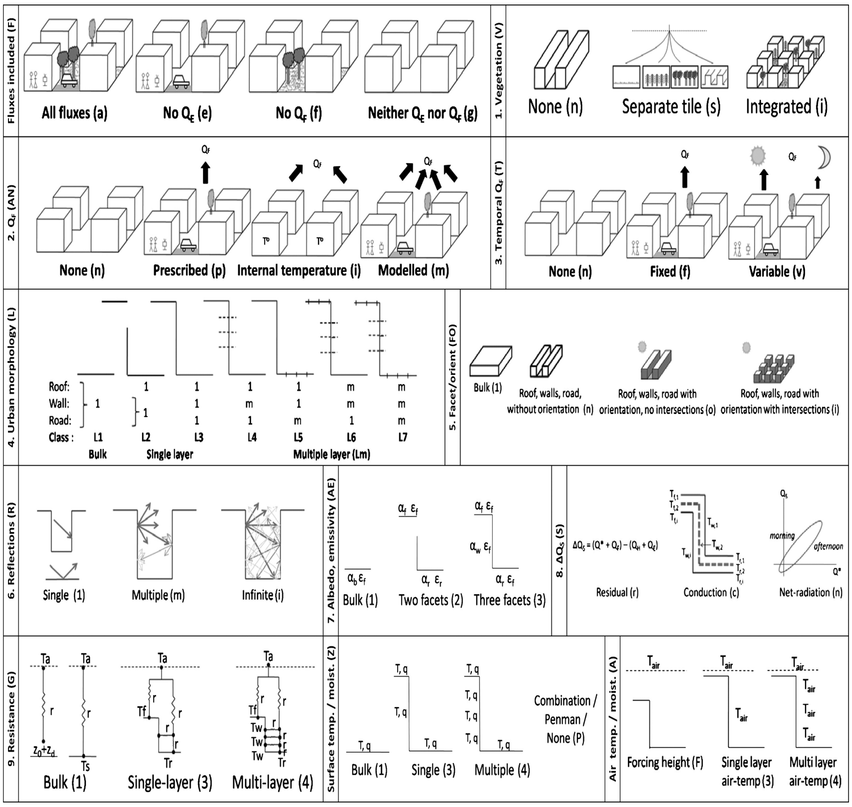

Figure 6: Characteristics used to classify models (Grimmond et al. 2010, p. 1270)

4.1.3 Micro-scale

Micro-scaled modelling brings resolutions down to a city block (and greater) scale, with the most detailed models resolving down to a few metres. Modelling at this scale presents special challenges. As with meso and local scaled models, micro-scaled models must also choose characteristics of urban environments (Figure 6) to determine the approach taken in modelling. For example, in the case of Q_F (anthropogenic heat), the area, the time of year, and the usage of the area can potential have significant impacts on the modelling results. An area with large amounts of heat from traffic, air conditioner usage, and other sources of anthropogenic heat compared to one with different or small amounts of anthropogenic heat will require consideration whether the approach chosen to model it best suits these factors.

Some models calculate most or all of the fluxes given starting conditions of temperature, wind speed, soil moisture, and time of year, such as ENVI-met. Other models, such as LUMPS/SUEWS, at the local scale, use basic meteorological data sets including observed temperatures, humidity, wind speed, and incoming shortwave radiation (and optionally other fluxes such as anthropogenic heat), and calculate the partitioning of those into flux components (sensible heat, heat storage, and latent heat). Models can also be coupled to a larger scaled model to provide either starting boundary conditions or ongoing meteorological forcing data.

4.2 Modelling strategies

4.2.1 NWP

Numerical weather prediction (NWP) models solve a series of differential equations using current weather conditions to predict future weather conditions. However, resolution of NWP is generally not sufficient to resolve urban areas. The designed resolution is generally global or regional. With tile or mosaic surface exchange schemes parameterisations, it is possible to model a percentage of a gridbox which contains the urban surfaces. However, results can only be seen at next level up, not at the urban level. Also, resolving greater complexity within urban areas (i.e. flows around buildings) is generally not possible with NWP schemes (Best 2005). NWP models are designed for short term projection runs of days to weeks and are given very accurate input data of current weather conditions at the beginning of a run.

4.2.2 GCM

Atmospheric general circulation models (GCM) are a general class of models, modelling radiation, heat, water vapour and momentum fluxes across the land-surface atmosphere interface. GCM models can be similar to NWP models both in design and modelling code, but GCM models are longer running (months to years) and incorporate a large number of interactions (atmosphere, oceans, ice, and land), some of which might have been parameterised in NWP runs.

4.2.3 Parameterisations

When some processes cannot be directly modelled, being smaller than the grid resolution of the model, or for model efficiency, estimates of values are made, based on observations (or other means of estimating reasonable values) instead of being calculated, this is called model parameterisation.

4.2.4 LSS

Land surface schemes (LSS) are designed to calculate the temporal evolution of energy and fluxes between land and atmosphere. Implementations can vary greatly in complexity. The simplest will treat the land as flat bare soil. Complexity can be added accounting for soil and vegetation interactions. The most complex will incorporate processes of photosynthesis and respiration (PILPS 2011). LSS will generally be a module within a modelling framework, in which each module handles a particular type of interaction.

4.2.5 CFD

At micro-scales, techniques of computational fluid dynamics (CFD) can be used to model flows around an urban landscape, including features such as buildings and trees. This is a ground-up approach (as opposed to GCM), starting with the smallest interactions at a detailed level and building those up to a larger picture. Mathematical models used in this technique are based on the Navier-Stokes equation, which describes the motion of fluids. This equation is solved in three different ways, Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), or Reynolds Averaged Navier-Stokes (RANS). DNS attempts to solve all the spatial scales within the flows and as a consequence is generally far too computationally intense for all but the smallest simulation. LES reduces the computational intensity through low-pass filtering, that is, filtering out the smaller scale pieces of the solution and concentrating on the larger scaled pieces. RANS uses mathematical techniques to simplify solutions of Navier-Stokes by separating fluctuating and averaging pieces (Yamada & Koike 2011).

4.2.6 Penman-Monteith equation

The Penman-Monteith equation is used to calculate net evapotranspiration (E) from an open area of vegetation. It is provided radiation levels, temperature, humidity, and wind speed using commonly available weather records. Different types of vegetation surfaces will have different values for aerodynamic resistance (R_A) and surface resistance (R_S), yielding evapotranspiration values appropriate for those surfaces (Penman 1948).

5 Modelling goals

5.1 Modelling WSUD

Quantifying the positive impacts of WSUD on human thermal comfort in urban areas requires a tool set. Observational studies are important in order to understand the processes within current urban areas and to provide baseline validation data sets for other studies. However, observational data is time consuming and difficult to collect, and can only study existing urban morphologies. Modelling tools are required to study many variations of features of an urban area (buildings and materials and orientations, vegetation, surface types, and water features) in the present and projected into the future.

WSUD impacts can be looked at in a number of ways and at different scales. While the main goal of the Cities as Water Supply Catchments program is increased water security and water filtration, quantifying the possible human thermal comfort benefits due to increased evapotranspiration through increased water and vegetation in urban canyons is desirable. Modelling the increased amounts of latent energy fluxes, increased shading from trees, and differences attributable to conversion of impervious surfaces to pervious can quantify the possible benefits to HTC of these changes. Understanding the changes in warming and cooling patterns across daytime and night-time can help combat effects of UHI. Also, understanding if increased numbers of trees and other obstacles will lead to changed wind flow and lead to reduced cooling through mechanical mixing is also important.

5.2 Modelling HTC

Human thermal comfort is a subjective experience for each individual based on a number of factors, however research has come up with methods to measure and quantify these. Environments can be analysed and general conclusions be drawn about levels of HTC (Figure 7). Determining factors include air temperature and humidity levels, but also include wind velocity, clothing, and activity levels (Olesen 1982). Human comfort depends on maintaining a body core 37C temperature through a combination of outside temperature and humidity with heat loss through wind and different levels of clothing and heat gains through radiation levels and metabolic rates influenced by different activity levels. Scales of HTC such as physiologically equivalent temperature (PET) or predicted mean vote (PMV) can rank conditions on a relative scale of too hot to too cold. Models, in order to be useful in quantifying HTC benefits of WSUD, will then need to provide data for variables including air temperature, radiant temperature, wind speed, and relative humidity.

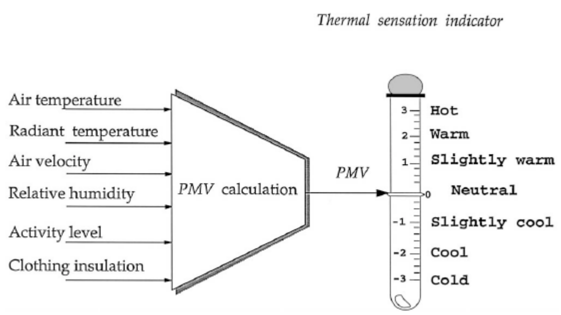

Figure 7: PMV and thermal sensation (Hamdi et al. 1999, p. 168)

5.3 Micro vs. local and meso scale

A micro-scale view allows resolution of temperature gradients in detail across an urban canyon over short distances (metres). Locating hot spots and cool spots, as well as running a number of different scenarios to find optimal numbers and arrangement of features can lead to determining best practice in using WSUD for HTC. Applying micro-scaled models to streetscapes or city blocks can bring these variations to a human- and building-scaled level (Figure 5-1,2).

With local and meso scale modelling, average effects over a wider area can be seen (Figure 5-4). Individual urban canyons will not be resolved, as individual grid squares (kilometre resolutions) will encompass entire neighbourhoods or cities. This scale will be more appropriate to see larger patterns of UHI effects as well as temperature trends across a daily cycle and broader views of the impact that different WSUD scenarios can have in their mitigation.

6 Micro and local-scaled models

A survey was conducted of all available models with a potential to model urban climates. This section will detail the models found, both micro scaled and local scaled which can be used or applied to meso-scaled modes, and their suitability to the application of modelling WSUD features in an urban area.

6.1 *Micro-scaled models*

6.1.1 SOLWEIG

SOLWEIG (SOLWEIG 2011) is a model that simulates spatial variations of mean radiant temperature and 3D fluxes of longwave and shortwave radiation. It features a GUI front end which allows a click through configuration of settings and dataset loading for a model run. It is built on top of MATLAB. The model domain is set up by using GIS Digital Elevation Models (DEM) to define the area to be modelled (land surface, buildings, building heights, etc.). A second optional DEM can be used to define the area's vegetation.

The GUI wizard steps the user through loading the DEM and selecting a single point of interest in the area (for more detailed output at that location). The model calculates shading across the area over a day. The model requires a small number of parameters (average albedo and emissivities of buildings and the ground). The model is driven by a meteorological data file (temperature, humidity, and incoming shortwave radiation). The model runs extremely quickly and produces output such as Figure 8, a test run of an area on the Monash campus.

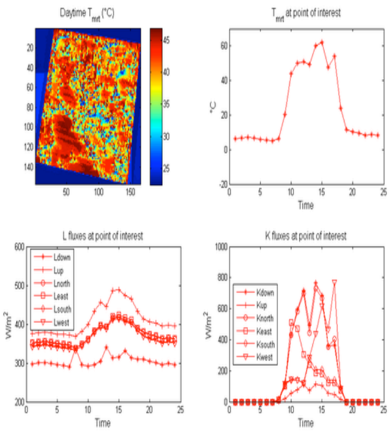

Figure 8: SOLWEIG output - plots of temperature and shortwave and longwave fluxes at a single point of interest

For strengths and weaknesses, firstly, the configuration is easy, using GIS data sets through a point and click GUI. It only models longwave and shortwave radiation fluxes, but validations of the model indicates that this simple approach captures *Tmrt* fluctuations (an important variable in calculating HTC) reasonably accurately (Lindberg & Grimmond 2011; Lindberg et al. 2008). The vegetation model is simplistic, using trunk heights and canopy types to calculate shadow zones. Surface temperatures of the vegetation are also assumed to be equal to the ambient air temperature. The model is freely available to be downloaded, running on top of a Java runtime (available from java.com), and the freeware MATLAB Complier Runtime. The model's source code is also available for research purposes.

As a highly simplified model, some of its limitations in modelling WSUD features become apparent. Parameters such as albedo and emissivities are not configurable for individual features. Temporal resolution is only one hour. Physiologically equivalent temperature (PET) calculations are not currently included. All surfaces in SOLWEIG are treated as impervious. Wind and water in general are not considered in the model. Vegetation is only treated as something that casts shadows.

The SOLWEIG development team anticipates future improvements, including a simple land use scheme as well as calculations of PET. This model would be able to quantify some of the thermal benefits of WSUD features, through vegetation shading, but is unable to quantify the cooling effects of water in an urban area, so will only have limited use in fully quantifying these benefits.

6.1.2 TUF-3D

The Temperatures of Urban Facets in 3D (TUF-3D) model simulates energy balances through a 3D raster model. TUF-3D uses separate modules to model radiation, conduction, and convection in order to predict fluxes of sensible heat, conduction, and radiation fluxes. Multiple reflections of solar radiation are included. Shading is calculated. Convection has been simplified into a 1D equation instead of more computationally intense methods such as large eddy simulations (LES) or Reynolds-averaged Navier-Stokes (RANS) (see section 4.2.5). The model is 3D in radiative exchanges only (Krayenhoff & Voogt 2007).

The model is written in Fortran (source code available for research purposes) and can be compiled and run in Linux or Windows. An average model run takes about 30 minutes for 24 hours of data. It has recently been extended to study different surfaces (grass, asphalt, concrete, and Astroturf) within urban canyons and model latent energy fluxes. Despite a simplified computational approach, published validations prove reasonably accurate (Yaghoobian et al. 2010). However, these additions of latent energy fluxes haven't been thoroughly validated through observational data (as of 2010).

While latent heat fluxes are modelled, the model does not fully account for effects of vegetation (water flow from soil through plants, respiration, and photosynthesis) within micro-scale climates. This is an important missing piece which limits TUF-3D's ability to fully model the impacts of WSUD features at a micro-climate level. However, once full vegetation modelling has been added (planned for the near future), TUF-3D should serve as a useful tool in WSUD modelling at these scales.

6.1.3 MIMO

MIMO was originally designed to model microscale wind flow to look at pollution dispersion in urban areas (Kunz 2000). It is based on computational fluid dynamics (CFD) using Reynolds-averaged Navier-Stokes (RANS) equations (see section 4.2.5). It is designed to be coupled with MEMO (a mesoscale model) to set initial states and boundary conditions, but doesn't use feedback (Ehrhard et al. 2000). The development team is interested in collaborations in research but given the complexity of the model (as well as intellectual rights issues), is not available outside of a research context. The complexity of the model along with the conditions of use limit this models use in wider modelling of WSUD features.

6.1.4 MITRAS

MITRAS (Mikroskaliges Chemie, Transport und Strömungsmodell) is being developed at the University of Hamburg based on the mesoscaled model METRAS. It is non-hydrostatic, solving equations for wind, temperature, and humidity, as well as pollutants. Calculation of shading effects are also included. It is based on computational fluid dynamics (CFD) (see section 4.2.5) using Reynolds-averaged Navier-Stokes (RANS) equations (Hinneburg et al. 2003). It can be nested with the mesoscaled model METRAS to set initial states and boundary conditions (Schlünzen et al. 2011).

It has mostly been used to model wind flows and pollution dispersion. It has modelled local-scale temperature gradients and their effects on circulation in an urban canyon (Bohnenstengel et al. 2004). It models the full water cycle including cloud formation and precipitation. The thermodynamic pieces of the model (shading/incoming radiation and evaporation from different types of green) are currently being improved. However, as with MIMO, the complexity of the model as well as IP issues means the model is not available outside of research project contexts. This again limits the suitability of this model for modelling WSUD features.

6.1.5 ENVI-met

ENVI-met (Bruse 1999) is a three-dimensional non-hydrostatic model based on CFD solving of Navier-Stokes equations using finite difference numeric methods (see section 4.2.5). It is designed to resolve a domains of 60x60 to 250x250 using grid squares of 0.5 m to 10 m. The model is available from the ENVI-met website (Bruse 2011) as freeware. However, the model is closed source and only available as a precompiled Windows executable file. ENVI-met provides an extensive set of modelled variables describing energy fluxes (longwave, shortwave, sensible and latent), weather conditions (temperature, wind, humidity) at different levels of the domain (2D surface points as well as 3D atmospheric points) and can use a variety of features (buildings of different materials, different types of vegetation, pervious and impervious surfaces of different types, and configurable layers of soil moistures). Mean Radiant Temperature and Predicted Mean Vote (PMV) are also available. An average model run will run in nearly real time, that is 24 hours of simulation will require 24 hours of computation.

ENVI-met is easy to configure and run, supplied with configuration editors, allowing graphical generation of domains (area, buildings, vegetation, and surfaces) as well as a GUI wizard to set up and run model runs. It also has a GUI to generate graphs from the results. The result sets include virtually all the variables necessary to resolve impacts to human thermal comfort using different WSUD techniques and tools are provided to export data from the extensive result sets.

Difficulties arise when trying to examine the results in detail and in ways other than the developers have provided. The output files are proprietary binary files which require reverse engineering to access the data directly. More importantly without available model source code (or active developer support), troubleshooting modelling results is difficult.

ENVI-met has been used in a number of published studies where there was an attempt to validate ENVI-met results. Alitoudert & Mayer (2006) found that the values predicted by the model were probably overstated due to higher than expected radiation fluxes predicted by the model. Krüger et al. (2011) focused on wind speeds as a validation for ENVI-met's accuracy and found initial wind speeds of greater than 2 m/s to be unreliable and a limitation. Spangenberg et al. (2008) showed average air temperatures and diurnal amplitude were lower than expected when compared with observed results and had to adjust the simulation's starting temperature and wind speed to bring the results into agreement in the morning and evening hours. In all these cases, the results were considered to be sufficiently accurate, or that the modelling difficulties were in areas considered less important in their core research problem.

In validations in research projects at Monash, reproducing spatial temperature gradients, as well as temporal variations, seen in observational data with ENVI-met was challenging. As ENVI-met is unable to use external forcing data, the relatively static weather conditions (wind and humidity) predicted by ENVI-met might have had an impact on the modelled results, being unable to drive variability seen in observational data. The model is slow to warm up during the day and slow to cool down at night, under-predicting daytime maximums and over-predicting night time minimums. Modelled temperatures varied from 2 to 6C from observed values. An overly simplistic soil/plant/atmosphere module might contribute to the difficulty in validating latent energy values predicted by ENVI-met. Diagnosing exact causes for divergences is difficult without model source code. As latent energy flux modelling is critical for evaluating the benefits of WSUD features, ENVI-met's utility in modelling WSUD will be limited until further investigation can find reasons for the inaccuracies.

6.1.6 CFD frameworks

A final approach to micro-climate modelling taken particularly by a number of researchers in Japan is hand-coding simulations using CFD frameworks such as OpenFOAM (OpenFOAM 2011) or STAR-CD (CD-adapco 2011). These frameworks provide C++ libraries to solve a wide variety of CFD related problems such as incompressible/compressible flows, particle tracking flows, and heat transfers as well as methods to create customised solvers. Meshes of various types are provided to be configured into any shape with any number of faces and edges in order to represent features in the simulations.

Computational wind engineering (CWE) techniques were designed to accurately model processes such as wind load on buildings, particle dispersion, and heat and moisture movement, all in small domains (under 1 km) (Mochida et al. 2010). Published reports of micro-climate modelling through these techniques report detailed and accurate results. Emphasis in these studies is generally centred around wind and particle dispersion, but fluxes which influence these flows are sometimes also added, along with features such as vegetation and the impacts they have on these flows. Nesting them within meso-scaled climate models to provide boundary conditions can add further accuracy to the simulations (Yamada & Koike 2011).

However, as with MIMO and MITRAS, the same issues of availability exist. Also, many of the scenarios are hand coded to exactly the modelled simulation and do not lend themselves to general usage. Writing a micro-climate tool for WSUD modelling using these frameworks would be a major undertaking. Also, these modelling techniques are very computationally intense.

6.1.7 Micro-scaled conclusions

The modelling of micro-scaled climates is a very young endeavour. It is gaining much attention and effort as the need to understand the micro-climates of urban areas to understand many aspects of the urban environment is becoming more apparent. Currently, no available model exists that is able to address the specialised requirements in modelling WSUD features. Accurately modelling the soil/plant/atmosphere interactions and the movement of water through those layers is the critical piece missing in most. Some models such as SOLWEIG might have some utility in looking at shading issues in urban canyons. Other models, such as TUF-3D need additional modules to be completely suitable. It is just a matter of time before a number of models are completed and made available for use, as there is a growing interest level in this area driving research, but currently there is not a suitable tool available for modelling WSUD features at the micro-scale.

6.2 Local and meso scaled models

6.2.1 Local scale introduction

A complete picture of the effects WSUD features can have on urban climates requires examining it from a number of different levels. While micro-scaled modelling is appropriate when examining a single urban canyon, issues such as UHI require a wider view to see the differences between different built up areas as well as the additive effects of multiple design decisions across a wide scale. Local scale models are often of the scale of around 1 km. In meso-scale modelling (e.g. city wide modelling of the UHI), the city is broken into 1 km tiles and the model is often coupled to an atmospheric model.

At these scales, in modelling WSUD features, models need to account for water usage and latent energy fluxes as they will be be an important consideration in whether they can accurately reflect what happens to an urban area when more water and vegetation is introduced. At a local (and meso) scale, *Tair* (air temperature) will be a good indicator of these impacts. Also, wind speeds and humidity levels will allow calculation of PMV/PET levels (see section *5.2*), although this measure is more useful at the micro-scale level.

6.2.2 TEB

Town energy balance (TEB) is both a model and a general approach to modelling urban areas. It starts with a canyon, dividing the urban energy budget across three surfaces (roofs, walls, and road). Two more surfaces can be added for snow on roofs and roads. Buildings are all of the same height and width. The buildings are along identical roads that has a length greater than width. Any road orientation is possible in the scheme. Sun and shade on walls and road is considered every 30 or 45° using 4 or 6 budgets each (Masson 2000). Meso-scale models such as WRF (section 6.2.4) have incorporated the TEB model in as a module to the larger model. Other models such as CABLE (section 6.2.7) have reimplemented the modelling approach as an urban module in their model. These will be discussed in those sections.

6.2.3 LUMPS/SUEWS

Local-scale Urban Meteorological Parameterization Scheme (LUMPS) is a local scaled model. It would fit best in the smaller portions (urban area or suburban area) of Figure 5-4 (1 km and larger). It uses a simple approach to model the surface energy balance (SEB) of an urban area. SEB schemes use the surface radiation budget equations (detailed in section *3.1*) to calculate missing terms, generally sensible heat flux(Q_H) and latent energy fluxes (Q_E). Given meteorological values for net radiation, temperature, humidity, wind speed as well as surface and land cover breakdowns, partitioning of other fluxes is calculated using a variety of strategies (Grimmond et al. 2010). Q_H and Q_E are partitioned from the available energy, using a version of the Holtslag & Van Ulden (1983) combination type model with coefficients determined for urban areas (Loridan et al. 2011).

Net all-wave radiation (Q^*) is calculated from the meteorological data. The objective hysteresis model (OHM) scheme is used to calculate predicted storage heat fluxes (ΔQ_S). In areas with a complex mix of surface types and covers, such as an urban environment, determining ΔQ_S can be difficult. OHM uses input of net all radiation levels and a detailed breakdown of surface cover (built and vegetation) (Grimmond et al. 1991). In modelling a 3-D structure of an urban canyon, ΔQ_S can not be modelled as a simple fraction, the (a) of the net all wave radiation relationship (i.e. $Q_G=aQ^*$), because thermal inertial does not lead to a linear relationship between the variables. OHM incorporates a phase difference (hysteresis) and adds a time factor into the different types and orientations of surfaces in the urban environment (Arnfield & Grimmond 1998). Using this strategy, the accuracy of the calculated ΔQ_S shows great improvement over the simple fractional method used by a large number of meso and global scaled models.

Surface Urban Energy and Water Balance Scheme (SUEWS) uses some of the modules from LUMPS, but adds additional urban water scenarios. Figure 9 shows the model's structure and order of calculations. Of most importance in modelling WSUD features, SUEWS accounts for soil moisture and drainage, surface and soil runoff, irrigation scenarios, and a wider set of surface cover and vegetation types. This allows the model to calculate latent heat fluxes using the Penman-Monteith equation (Grimmond & Oke 1991) (see section 4.2.6).

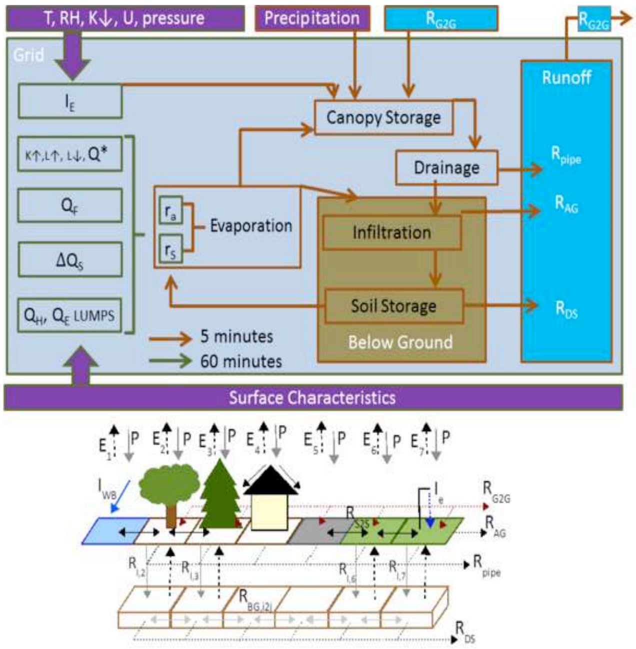

Figure 9: SUEWS order of calculations (Järvi et al. 2011)

SUEWS is a precompiled Windows executable file. Model runs require a predetermined directory structure containing a number of required input and configuration files. The model allows linkage of separate grid areas in order to model water flow between them. For example, an area might contribute water to another area through pipes or runoff. Overall properties such as albedos, leaf area index (LAI), bulk surface emissivity for various surfaces are set. Also, choices between whether variables Q_F (anthropogenic heat), ΔQ_S (heat storage), $L\downarrow$ (incoming longwave), and Q^* (net radiation) are calculated or given, as well as the source of vegetation configuration information.

SUEWS requires meteorological forcing data for simulations, requiring at a minimum wind speed, relative humidity, air pressure and mean air temperature. The model also allows settings of properties for pervious and impervious surfaces to account for water movement, runoff and drainage. Other configuration settings allow accounting for water irrigation introduction and choosing between different methods of calculating net storage heat fluxes through OHM. A GIS input data file can provide the breakdown of surface cover (i.e. buildings, grass, vegetation, concrete, pavement, etc.). For output, the model provides a breakdown of energy fluxes, surface temperature, and water levels in different features at 5 and 60 minute intervals (Järvi et al. 2011).

In terms of modelling WSUD features, some features are not directly accounted for in the model. A tree/biofiltration feature would need to be modelled through the changing the overall percentages of vegetation, pervious surfaces, and ground moistures and available water in an area. An international survey of urban energy balance models concluded that no model has best performance for all fluxes yet (Grimmond et al. 2010). Further, it concludes that modelling latent energy has been the most problematic. It is often not included in urban energy balance models, yet is a critical inclusion for accurate results in modelling WSUD features. SUEWS' inclusion of latent energy fluxes as well as irrigation and runoff is an important inclusion. Validations by the model's authors showed that the model is able to simulate net all-wave radiation, turbulent sensible and latent heat fluxes compared to observed values. They did find that it underestimates latent heat fluxes and overestimates sensible heat fluxes during the day. However, they concluded that it is suitable to model planning scenarios for water usage and landscaping as well as looking at climate change mitigations (Järvi et al. 2011).

A preliminary validation of SUEWS using the Preston data set (Coutts et al. 2007) from April 2004 shows findings consistent with the results reported above by the model's authors. Modelled latent energy fluxes tend to be slightly low while sensible heat fluxes tend to be slightly high when compared to Preston reference results (Figure 10). As these results are only preliminary, further investigation is needed to find the proper settings for these model runs.

Coupling LUMPS/SUEWS to a boundary layer model is also possible and will allow a wider range of scenarios to be run, using realistic weather forcing data. One limitation is that it does not provide T_{air} predictions and a simple 1-D boundary layer model might be needed as supplement.

There is potential for integration with other models (e.g. inclusion in the Cities' toolkit) such as the urban planning model and will allow end to end automated assessments of HTC based on modelled changes in planning policies. Based on all these different factors, LUMPS/SUEWS would be a good tool to model larger impacts of WSUD (as well as urban heat island effects) on a local scale.

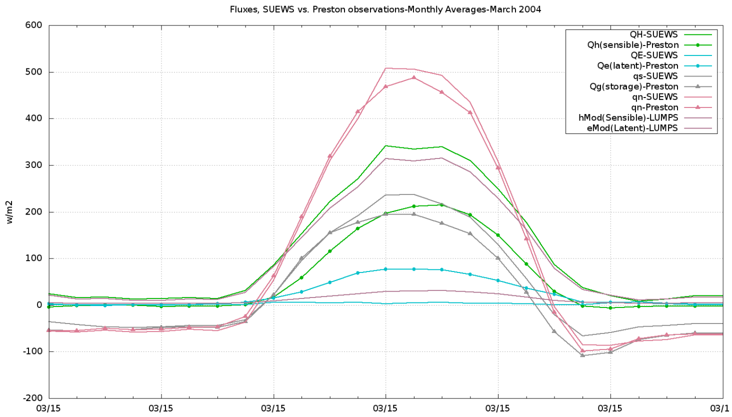

Figure 10: LUMPS/SUEWS comparison to Preston observations, April 2004

6.2.4 WRF

The Weather Research and Forecasting (WRF) model (Chen et al. 2004; Kusaka et al. 2001) is a non-hydrostatic, compressible meso-scaled model. It uses a column single-layer canopy model for energy and momentum exchange between the urban surface and the atmosphere. WRF includes the Noah land surface model (LSM) in order to provide surface sensible and latent heat fluxes, and surface skin temperature as lower boundary conditions. The use of CFD based methods to model flows around individual buildings in the urban canopy module (UCM) was considered too computationally intense, therefore, this variability was parameterised and simplified into a more heterogeneous urban landscape.

Urban canyons are parameterised into a simplified 2-D symmetrical infinite lengthed geometry. This is used to calculate 3-D radiation fluxes within the canyon. Water is modelled using a simple 'very thin bucket scheme', that is surfaces are treated as impervious and well drained. A single layer vegetation model is used to calculate latent energy fluxes. Much of the detail of urban areas is lost at the coarser scales the models resolves, so these simplifications are not considered a major problem.

The coupling of LSM and urban model in WRF is accomplished through setting percentages of surfaces and features. The LSM calculates fluxes and temperatures associated with vegetation and the UCM module calculates those for the man-made surfaces.

In modelling the impacts of WSUD, WRF has some potential at a meso scale. Its resolution is most suitable to model the combined urban and suburban areas of Figure 5-4. Detail at a street or neighbourhood level is not possible, the best resolution that can be resolved is ~2 km grid squares. In comparison to LUMPS/SUEWS, the resolution is much coarser. At this scale, information about roof, wall, and road surface temperatures, with varying amounts of water and vegetation and differing land uses within the region will be averaged across a larger area, but can still help investigate strategies to mitigate effects of urban heat island as well as addressing human thermal comfort issues.

6.2.5 CCSM

The Community Climate System Model (CCSM) (Vertenstein et al. 2004) is a global scaled coupled climate model containing modules for simulating atmosphere, ocean, land surface and sea-ice, and one central coupler component, the CCSM. Of these, the land component, Community Land Model (CLM) is the important one for potential modelling of WSUD features in an urban context. An urban module has been integrated within the CLM module (Oleson et al. 2008a; 2008b) and can be coupled to the atmospheric model (Figure 11). The urban module is based on TEB (see section 6.2.2).

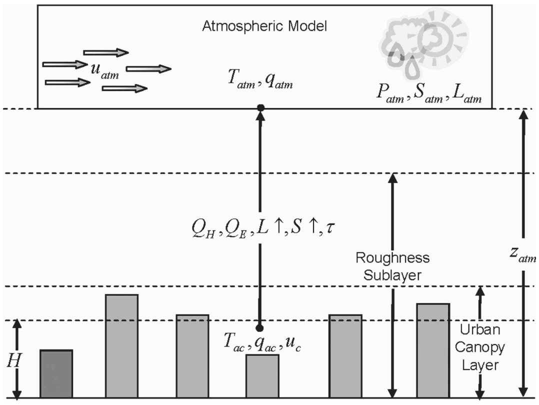

Figure 11: Schematic of urban and atmospheric model coupling (Oleson et al. 2008b, p. 1040)

Its resolution would be most suitable to model the combined urban and suburban areas of Figure 5-4. Its resolution is comparable to that of WRF, that of meso to regional scaled, and coarser than LUMPS/SUEWS. CLM can also run Single-Point/Regional cases (PTS_MODE), using the latitude and longitude of the point to be modelled (Kluzek 2010). Urban canyons are accounted for in the CLM module, however average values for fluxes and temperatures in the centre of the canyon will be returned (Figure 12), as opposed to detailed information about temperatures in each part of the canyon. As with WRF, CLM can help investigate wider spread impacts of WSUD features through the modelling of modifications of amounts of water and vegetation in urban areas.

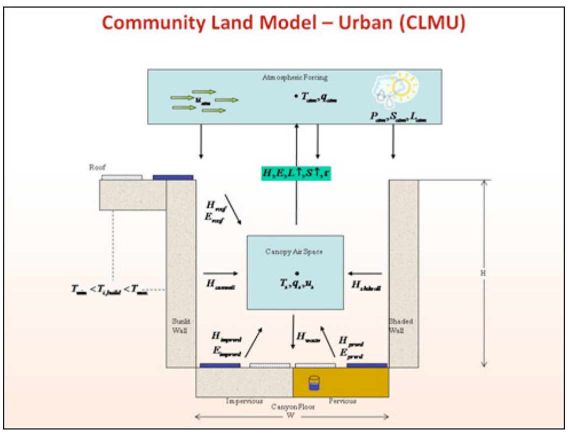

Figure 12: CLM urban canyon modelling (UCAR 2011)

6.2.6 JULES

JULES (Joint UK Land Environment Simulator) is based on MOSES (Met Office Surface Exchange System), the land surface model used in the Unified Model of the UK Met Office (UK Meteorological Service). The uses of the model have grown, from its original purpose to represent land surfaces to expanded uses of predicting river flows, identifying global wetlands, and quantifying water resources. Due to these expanded roles, MOSES was spun off into the JULES community model project to develop the model independently of the meteorological and climate model (JULES 2011).

The model uses a NWP (section 4.2.1) strategy (Best 2005). This meso-scaled model has a horizontal resolution of about 12 km (Figure 5-4), comparable to that of WRF and CCSM and coarser than LUMPS/SUEWS. JULES adds a highly simplified urban canopy module using a canopy of concrete to model radiation exchanges with the underlying soil (Figure 13). It uses the Penman-Monteith equation (section 4.2.6) to calculate latent energy fluxes. It uses a tiled scheme of heterogeneous surfaces in order to resolve urban area land uses. Each tile uses a small number of parameters (surface albedo, aerodynamic roughness length (z_{0m}), and heat capacity (C) (Best et al. 2006). This highly simplified urban scheme combined with a coarse resolution of urban areas means JULES could be used to examine average effects over large areas of land use changes and increases in water and vegetation but is less suited toward investigations of human thermal comfort impacts of WSUD features within urban areas.

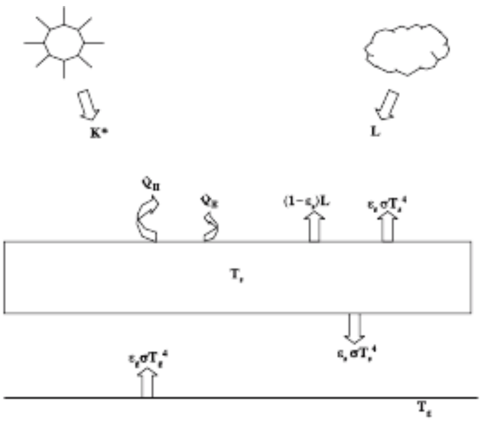

Figure 13: Surface energy balance of MOSES urban canopy model (Best et al. 2006, p. 506)

6.2.7 CABLE

The CSIRO Community Atmosphere Biosphere Land Exchange (CABLE) model consists of a atmospheric general circulation model (GCM) (see section 4.2.2) and land surface scheme (LSS) (see section 4.2.4) module. The LSS module simulates the exchange of radiation, moisture, heat, and carbon at the land surface. Using meteorological data input, it will predict radiation fluxes and CO_2 exchanges. It can be also be coupled to an atmospheric model. It has a complete implementation of vegetative processes (radiation transfer, stomatal conductance, and photosynthesis) modelling (Kowalczyk et al. 2006). It also has a recently added urban canopy module, based on a TEB (see section 6.2.2) approach.

CABLE's resolution would place this model in a similar domain (Figure 5-4) to that of LUMPS/SUEWS with resolutions down to 5 km, and possibly down to just over 1 km. Unlike SUEWS, it does not feature specialised water usage scenarios. However, the addition of the TEB module to its already complete implementation of vegetative processes, is suitable to model impacts of WSUD features on a broad scale.

6.2.8 Local and meso scaled conclusions

At a local and meso scale, investigation of impacts of WSUD features in urban areas will necessarily focus on wider spread average effects. Of the available models running at this scale, LUMPS/SUEWS contains the most specialised scenarios to account for water usage in urban areas and is best suited for this purpose at a local scale. CABLE, also at a local scale, is less specialised but would also be suited to an investigation of factors in

HTC in urban areas. The meso scaled models, WRF, CCSM, and JULES, have application at a wider scale, looking at average effects, but could see their suitability limited, as in the case of JULES, by a highly simplified urban approach, leading to much more average results between urban and rural areas.

7 Conclusion

In choosing climate modelling tools for the Cities as Urban Catchments project, looking at a variety of aspects of impacts of WSUD on HTC in urban areas requires a number of different tools. At a micro-scaled level, there is currently no available model suitable to address this specialised requirement. Models exist to address some of the concerns (that of shading effects from vegetation) but none to model the entire soil/plant/atmosphere interaction and the part water plays in this. Waiting until a model does emerge is possible, as there is a growing research interest in this space. Another course of action is to complete an existing model (such as TUF-3D) to add the required capabilities. This option is currently being explored.

However, at a local (and greater) scale, more options exist. A number of meso-scaled models are available to look at broad scale effects of WSUD design, WRF and CCSM being most suitable at this scale. At a scale in-between meso and micro-scaled, the two local scaled models LUMPS/SUEWS and CABLE contain enough features to model water and vegetation effects of WSUD at a neighbourhood scale. With its specialised urban water usage scenarios, SUEWS is the most suitable model in this scale, especially with some additional work to link it into other modelling tools in the Cities' toolkit.

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