Assessing the impacts of temporal resolution of precipitation forcing data on the surface energy and water balance

Tan Yin San

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ABSTRACT

In urban climate research, spatial and temporal variability of precipitation is always a critical element for numerical modelling. However, the effects of temporal resolution of precipitation forcing data has received little attention. Moreover, there has always been a difference practically and theoretically in the availability of precipitation data. This study was carried out to assess the impact of temporal resolution of precipitation forcing data on the modelled surface energy and water balance using available data from a site at the Strand campus of Kings College London. Analysis has been carried out using 5 minute rainfall data as a reference, compared with rainfall data accumulated to various temporal resolutions. The results suggest that as the temporal resolution of precipitation forcing data decreased, there are significant impacts on the modelled output depending on the timing of rainfall occurrence, rainfall intensity and the rainfall duration. The modelled evaporation and runoff, as well as other variables such as the turbulent heat fluxes, tends to deviate from referenced rainfall data. For days with daily total rainfall amount more than median but less than maximum, results shows more significant impacts on the modelled surface energy balance and water balance. Under conditions of no rain, as expected, the impacts of temporal resolution were less significant. This study highlights the importance of high resolution precipitation forcing data in urban areas for modelling for a wide range of applications.

Keywords: SUEWS model, urban water balance, temporal resolution, precipitation, London
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CHAPTER 1 INTRODUCTION

1.1 General

Precipitation plays an important role in both the energy balance and water balance of the Earth climate system. Moreover, due to conditions of the Earth’s-Atmosphere state that can exist in three phase: gas, liquid and solid state, precipitation has become one of the important forcing data in surface energy balance and water balance. This unique physical properties enables the complete hydrological cycle (Bridgman and Oliver, 2006). Precipitation acts as one of the incoming sources of water input. The evaporation process requires energy to supply the latent heat of vaporization which makes the link between the energy balance and water balance. Variability of precipitation comprises a significant source of uncertainty in the weather and climate models (Berne et al., 2004; Fekete et al., 2004; Aronica et al., 2005; Wang et al., 2009; Beck et al., 2015). It increases with the spatial and temporal resolution of precipitation forcing data. Evaluation of potential impacts on precipitation forcing datasets is an ongoing area of research in urban hydrological application, environmental science and climatology as well as for those climate change negotiator.

Life on Earth depends on the energy that comes from the sun in the form of shortwave radiation. The basic principle of Earth’s climate can be explained by considering the radiation energy balance of the Earth using a simple global mean energy balance model (Houghton, 1997). On average, this energy must be balanced by the outgoing radiation from the Earth and the energy reflected by clouds, snow, land surface state and etc. This outgoing energy can be in the form of longwave radiation and combination of the heat that come from latent heat or sensible heat. However, due to the expansion of human populations and growth of the cities, changes in sources of energy and how this energy is partitioned, this balance had been altered and leads to the development of special local climates, referred to as urban climates.
Urbanized areas represent one response of the natural environment to the human population growth. The wide range of land use practices, urban surface roughness and the response from additional energy sources has altered the thermodynamics of the surface energy balance, budget of heat, mass and momentum and the boundary layer (Grimmond and Oke, 1995; Offerle et al., 2005; Harman and Belcher, 2006; Coutts et al., 2007). Features of the urban climate such as urban heat islands (UHI) (Offerle et al., 2005; Harman and Belcher, 2006; Coutts et al., 2007), urban induced wind circulation (Grimmond and Oke, 1995) and precipitation enhancement downwind of urban areas (Zhong and Yang, 2015) are often undesirable, as they bring significant impacts in terms of human comfort levels, pollutant dispersion and flooding (Bridgman and Oliver, 2006). However, rapid growth of human population and population density, in turn, leads to the need for better living conditions.

Given this, there is a growing interest in quantifying the surface energy and water balance of urban areas by attempting a greater understanding of the complexity required by the existing energy and water exchange models (Grimmond et al., 2010). Urban surface energy and water balance models are critical components to understand urban climatology. Of particular interest in this research, is the Surface Urban Energy and Water Balance Scheme (SUEWS). It is a model that uses a small number of commonly measured meteorological variables (Järvi et al., 2011). Precipitation is the key forcing data that required accurate measurement to run SUEWS. Higher resolution data is expected to lead to a closer modelled urban climate forecast to real world conditions, and benefit in predicting human health under climate change. However, not all precipitation data are available in fine spatial and temporal resolution. As documented by Berne et al. (2004), given practical and financial reasons, there is often a discrepancy between what is needed for the model and actual rainfall measurements. Therefore, the impacts of temporal resolution of the precipitation forcing data used in the SUEWS model needs to be investigated and addressed.
1.2 Motivation of the study

Weather is a chaotic system (Inness and Dorling, 2013). Everyday changes lead to the alteration of the surface energy balance and water balance. Furthermore, these balances become much more complex due to urban factors. For example, increased surface roughness in urban areas induce the wind circulation which favours more convection and storm activities as the vertical velocities and vertical atmospheric mixing increases (Ramamurthy and Bou-Zeid, 2014; Zhong and Yang, 2015). Storm runoffs had increased (Xiao et al., 2007) due to more storm activities as well as increase of energy demands on additional air conditioning during the heat wave event (Mitchell et al., 2008). A model to predict weather is a numerical approximation. The model depends on initial values as well as the forcing input data used to run the model. Any small changes in either the initial values or input data could lead to divergence between the modelled output and the real-world conditions.

The objectives of this study are to extend the understanding of the urban surface energy and water balance, using the Surface Urban Energy and Water balance Scheme (SUEWS) for an area of London. From the literature review, it was found that most of the research that used SUEWS model focused on monthly, seasonal variability and annual changes on areas of interests (Grimmond and Oke, 1995; Järvi et al., 2011; Järvi et al., 2014; Kotthaus and Grimmond, 2014). Till now, there is no published research on the topic addressed in this study. This topic is the first study using model SUEWS to test the impact of temporal resolution against the modelled output. This project attempted to answer these three following questions:

1) How does the temporal resolution of the precipitation forcing data impact the SUEWS modelled surface energy balance and water balance?
2) Which resolution is best for capturing the temporal variation of precipitation?
3) Can 180 minute re-analysis data be used as forcing data for the model if the rainfall is assumed to be equally distributed over this period?
1.3 Structure of the dissertation

In the following chapters, a literature review on urban environments, urban characteristics and the surface urban energy and water balance framework is provided (Chapter two). Chapter three describes the area of study and methodology used for the input data. Chapter four presents the findings and discussions. Chapter five draws the conclusion of this study and provides recommendations for the future research.
CHAPTER 2  LITERATURE REVIEW

2.1  Surface urban energy and water balance framework

The Surface Urban Energy and Water Balance Scheme (SUEWS), version v2015a, is used in this study. This is a scheme that combines previously published energy and water fluxes models to simulate the surface energy and water balances at the local or neighbourhood scale ($10^2$ - $10^4$ m) (Järvi et al., 2011). This model minimizes the number of required meteorological input data (Table 1) so that SUEWS is able to operate on an individual basis. Information about the surface covers with the design of sub-models are as shown in Figure 1. This scheme includes both energy and water exchange processes by considering the complete urban hydrological cycle. In addition, urban evaporation-interception scheme adopted in SUEWS allows the simulation of urban evaporation which includes both evaporation and transpiration from plants such as grass, gardens and trees (Mitchell et al. 2008; Järvi et al. 2011). Other information required to run the SUEWS model, are plan area fraction of each surface type, number of inhabitants, fraction of irrigated area using automatic sprinklers and internal hydrological connectivity.

The conceptual framework for an urban areas, water balance of the external environment can be written as (Järvi et al., 2011):

\[ P + I_e + F = E + R + \Delta S \ [mm \ h^{-1}] \quad (1) \]

Where \( P \) is precipitation, \( I_e \) is external piped water supply, \( F \) is anthropogenic water emission (e.g. combustion, air conditioning, human emissions from breathing), \( E \) is evaporation (including transpiration), \( R \) is runoff, and \( \Delta S \) is net change in water storage (e.g. changes in soil moisture, detention ponds) within the area of study. The units for each term in Equation 1 are depth (mm) per unit time.
Table 1: Required (a) meteorological input and (b) output variables of the model. The spatial scale the data are representative of are: local scale or the whole grid (Loc) and individual surface types within a grid (T). Larger areas can be determined from the individual grids. (From: Järvi et al., 2011.)

The energy balance is linked to the water balance through evaporation processes. The energy balance is analogous to Equation (1) and can be written as (Järvi et al., 2011):

\[ Q^* + Q_F = Q_E + Q_H + ΔQ_S \quad [W \ m^{-2}] \] (2)
Figure 1: SUEWS (upper) order of calculations within a grid cell and between grids; (lower) conceptual diagram of the seven parallel surface types with the horizontal and vertical flows of water within a grid cell and between grid cells. $E$ is the evapotranspiration, $P$ the precipitation, $I_e$ the external irrigation, $R$ runoff. (From: Järvi et al., 2011.)

Where $Q^*$ is net all-wave radiation, $Q_F$ is anthropogenic heat emission, $Q_E$ is latent heat flux ($Q_E = L_v E$; $L_v$ is the latent heat of vaporization), $Q_H$ is turbulent sensible heat flux, and $\Delta Q_S$ is net storage heat flux which includes soil heat flux and also the heating and cooling of the complete urban fabric.

For completeness, the urban energy balance can be defined in terms of available energy, $A$, as sources of energy which can be written as:

$$A = Q^* + Q_F - \Delta Q_S \quad [W \, m^{-2}]$$

(3)
The spatial scale for SUEWS is primarily set as the neighbourhood or local scale. The temporal resolution for this model is set with a basic time step of 5 minute to hourly, the obtained output can be aggregated into daily, monthly and annual time periods.

As described by Järvi et al. (2011), by changing the surface characteristics and meteorological forcing, SUEWS can run from daily up to multiple years. In her research, Järvi et al. (2011) found that SUEWS is able to simulate the net all-wave radiation and reproduces the diurnal cycle of both the latent and sensible heat fluxes. However, SUEWS typically underestimates latent heat flux while overestimates sensible heat flux in the day time. As for the soil moisture content and the surface wetness state which is tested against measurements in Vancouver, SUEWS is able to respond correctly to short-term events and seasonal changes of the vegetation. She also found that the determination of surface conductance is the largest uncertainty for this model. For areas with higher vegetation cover, SUEWS modelled higher evaporation and lower runoff values.

The recent development of this model was published by (Järvi et al., 2014) where snow is included in the scheme so that this model is more applicable for cold climate cities. His research found that the developed model underestimates the total snow depth by 18-20% in a Helsinki catchment and 29-33% in a Montreal catchment. This is due to the uncertainties arising largely from estimating the timing of the melting period and the parameterization of the snowmelt. However, this developed model is still able to reproduce the exchange of energy and water during cold snow, melting snow and snow-free periods.
2.2 Precipitation

In urban climate studies, precipitation is one of the key elements in surface urban energy and water balance modelling because it is the key driver to the hydrological cycle. High time and space resolution of precipitation data are required for many applications. Accurate attributions of the precipitation are vital for human society as it allows improvement of water balance calculations. Improving water balance calculations can result in better estimates of storm water discharge, amount of renewable water available as water supplies, and waste water disposal (Mitchell et al., 2003; Xiao et al., 2007).

The key problem is that precipitation is highly variable in both time and space. As argued by Fekete et al. (2004) in his study, this key variable often has shown noticeable differences in temporal and spatial distribution regionally but agrees in terms of latitudinal bands and seasonal cycles. Since the precipitation is the major incoming source of water in the hydrological cycle, thus temporal and spatial resolution of precipitation data became one of the crucial variables in surface urban energy and water balance models. Previously published studies on the impact of temporal resolution of precipitation forcing data agree that finer temporal resolution of precipitation forcing data improves model accuracy and reliability of urban hydrology modelling (Aronica et al., 2005) and provides better performance in short-term river discharge estimation (Wang et al., 2009).

Variability of precipitation increases as the temporal resolution and spatial resolution increases (Beck et al., 2015). In his statistical analysis of sub-daily precipitation extreme in Singapore, Beck et al. (2015) highlights that the required spatio-temporal resolution of precipitation forcing data for numerical simulations is a function of concentration time. Thus, sufficient information on spatio-temporal characteristics of precipitation forcing data is required. However, in reality, researchers and decision makers often face the issues of insufficient spatio-temporal precipitation measurement. As a result, variability of precipitation has become a significant source of error in modelling, e.g. for flooding forecast (Wang et al., 2009).
Any small changes in the precipitation input data used result in a dramatic change in the runoff response (Fekete et al., 2004). Fekete et al. (2004) argued that using a very coarse temporal resolution of precipitation input data results in a systematic underestimation of peak runoff.

All the elements considered in the surface urban energy and water balance model refer to processes with different response times. For example, when rainfall occurs, the response time for runoff should be faster than the evaporation response time (Wang et al., 2009). Researchers and decision makers often face situations of lack of input data, e.g. poor reliability of station-based data due to sparse rain gauge density or poor quality of rainfall measurements with insufficient temporal and spatial resolutions (Fekete et al., 2004; Wang et al., 2009; Beck et al., 2015).

Although extensive research has been carried out on the effects of temporal resolution of precipitation forcing data on the rainfall-runoff model, for example impact on river discharge located in Japan (Wang et al., 2009), impact on urban drainage systems in Italy (Aronica et al., 2005), spatial and temporal resolution required for urban hydrology near French Mediterranean coast (Berne et al., 2004), impacts on runoff estimates globally (Fekete et al., 2004) but the hydrological modelling of both the surface urban energy and water balance model are limited. Thus, the effect of temporal resolution of precipitation forcing data on the modelled surface urban energy and water balance needs to be considered.

2.3 The urban environment

The urban environment has a major influence on local and regional climate. Table 2 summarizes the current understanding on the impacts of urban areas on the climate. Urban climate research has included research on energy exchanges (Grimmond and Oke, 1995; Kotthaus and Grimmond, 2014) and the importance of spatial scales at which urban geometry and surface materials vary (Arnfield, 2003; Harman and Belcher, 2006).
2.4 Characteristic of the urban area

Urban areas modify the physical properties of a local climate by altering the natural environment in terms of three categories - hydrologic, thermal and aerodynamic. Figure 2 shows the schematic of the urban boundary layer (UBL), including its vertical layers and scales. The variation of urban surface properties is the key in dealing with urban climate effects especially when dealing with urban climate modelling because urban morphology and materials also influences the energy, mass and momentum exchanges in the cities (Bridgman and Oliver, 2006).

<table>
<thead>
<tr>
<th>Property</th>
<th>Urban-rural comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness length (m)</td>
<td>Rural: 0.01–0.5; Suburban: 0.6–1.0; Urban: 1.5–2.5</td>
</tr>
<tr>
<td>Albedo</td>
<td>Rural: 0.12–0.20; Suburban: 0.15; Urban: 0.14</td>
</tr>
<tr>
<td>Emissivity</td>
<td>Rural: 0.92–0.98; Urban: 0.94–0.96</td>
</tr>
<tr>
<td>Thermal admittance (J m(^{-2}) s(^{-1}) K(^{-1}))</td>
<td>Rural: 600–2000; Suburban: 800–1700; Urban: 1200–2100</td>
</tr>
<tr>
<td>Anthropogenic heat (W m(^{-2}))</td>
<td>Rural: Nil; Suburban: 15–50; Urban: 50–100 (winter up to 250)</td>
</tr>
<tr>
<td>Condensation nuclei (cm(^{-3}))</td>
<td>Urban: 10(^5)–10(^6); Urban: 10(^4)–10(^6)</td>
</tr>
<tr>
<td>Aitken</td>
<td>Rural: 10(^5); Urban: 10(^4)–10(^6)</td>
</tr>
<tr>
<td>Cloud</td>
<td>Rural: 2500; Urban: 10(^3)–10(^4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Urban change compared to rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence</td>
<td>10–50% greater</td>
</tr>
<tr>
<td>Wind speed</td>
<td>5–30% less in strong wind; increased in weak winds with UHI</td>
</tr>
<tr>
<td>Wind direction</td>
<td>1–10(^\circ) variation, more in canyons</td>
</tr>
<tr>
<td>UV radiation</td>
<td>25–90% less</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>1–25% less</td>
</tr>
<tr>
<td>Infrared radiation</td>
<td>5–40% greater</td>
</tr>
<tr>
<td>Evaporation</td>
<td>~50% less</td>
</tr>
<tr>
<td>Convective heat flux</td>
<td>~50% greater</td>
</tr>
<tr>
<td>Heat storage</td>
<td>~200% greater</td>
</tr>
<tr>
<td>Air temperature</td>
<td>1–3 °C greater annual average; up to 12 °C hourly average greater</td>
</tr>
<tr>
<td>Humidity</td>
<td>Less in summer daytime; higher in summer night, winter day</td>
</tr>
<tr>
<td>Cloud</td>
<td>More, especially downwind of city</td>
</tr>
<tr>
<td>Fog</td>
<td>More or less depending on aerosol numbers; local environment</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>Greater, especially downwind of city</td>
</tr>
<tr>
<td>Thunderstorms</td>
<td>More</td>
</tr>
<tr>
<td>Snow</td>
<td>Less, turns to rain</td>
</tr>
<tr>
<td>Tornadoes</td>
<td>Fewer</td>
</tr>
</tbody>
</table>

Table 2: Impact of urban areas on climate compared to rural areas. (From Bridgman and Oliver, 2006.)
2.4.1 Hydrologic changes

As reviewed by Zhong and Yang (2015), urban land cover has significant impacts on rainfall patterns, amount and distribution. They found that the urban environment has significant impacts on rainfall climatology, increasing the frequency of rainfall over and downwind of major urban areas. In addition, modifications of land surface conditions delay the convective activities (Harman and Belcher, 2006) and influence the formation and movement of thunderstorms (Ramamurthy and Bou-Zeid, 2014).

Transformation of natural surfaces into artificial surfaces significantly modifies the ecosystem hydrological regime. For instance, the amount of surface runoff is limited on soil of a pervious nature where water can infiltrate. However, man-made ‘waterproofing’ or impervious surfaces, such as roofs, streets, buildings and parking lots, increases the surface runoff, reduces the infiltration rates and hence increases the total runoff water volumes (Griffiths, 1976; Xiao et al., 2007; Järvi et al., 2011).
Another urbanization impact is that of moisture availability via evaporation. Evaporation is the process of phase change of a substance from liquid state to vapour. Evaporation can occur at any surface of water bodies, from the soil surface or any types of moist surface states. Evaporation on the Earth surface is one of the major components of the hydrological cycles and vital in Earth surface water balance. Ramamurthy and Bou-Zeid (2014) showed that there were significant impacts of evaporative fluxes on urban surface energy balance particularly after a rain event. Their study showed that following the precipitation events, nearly 17% of total latent heat flux was from the impervious surfaces in urban areas during a wet 10 day period.

In the urban canopy, evaporation is reduced compared to natural soil and vegetation surfaces. When the evaporation decreases, the amount of moisture also decreases and hence the air becomes drier. As the air becomes drier, the ability of moisture level to act as sink to the pollutant in the air decreases. Thus, if the air stays drier for a longer period, the pollutant would easily disperse many thousand kilometres downwind (Bridgman and Oliver, 2006; Ramamurthy and Bou-Zeid, 2014).

However, the impact of urbanization on catchments has not had such clear results. Study by Mitchell et al. (2003) concluded that the components of water balance, which are created due to urbanization (imported water and wastewater), exert less influence compared to seasonal and annual variations in climate.

### 2.4.2 Thermal changes

The recent statement in the IPCC summary report for policymakers (IPCC, 2013) says that it is extremely likely that human influence has been a dominant cause of the observed warming since the mid-20th century. Anthropogenic activities in densely populated areas have released large amounts of waste heat, as well as carbon dioxide, into the atmosphere and altering the boundary layer climate. One of the notable thermal impacts of anthropogenic heat is that it contributes significantly to
the formation of the urban heat island (UHI) (Grimmond and Oke, 1995; Harman and Belcher, 2006; Bridgman and Oliver, 2006; Coutts et al., 2007).

The urban construction materials in a city have greater thermal conductivity and heat storage capacities which results in a surface that absorbs more solar radiation compared to rural surfaces. However, not all urban areas are always hotter, drier, or windier than surrounding rural landscape. As mentioned in an essay by Grimmond (2006) in Bridgman and Oliver (2006), the local climate processes in cities do vary and depend on regional setting (arid areas, tropical rainforests or coastal wetlands) and the city’s planning, adaptation and mitigation strategies.

Typically, studies have found that latent heat fluxes are smaller in urban areas than the rural areas (Harman and Belcher, 2006; Coutts et al., 2007). However, due to extra water provided by irrigation and extra energy provided by human activities, latent heat fluxes often become higher. While strong net storage heat fluxes and anthropogenic heat fluxes gained throughout the day, maintain the positive sensible heat fluxes that are released at night (Harman and Belcher, 2006; Kotthaus and Grimmond, 2014). As a result, the urban surface energy balance has been altered. Compared to rural areas, urban areas often have earlier peaks for net storage heat fluxes, while sensible heat fluxes often peak later in the day.

2.4.3 Aerodynamic changes

Other physical change induced by urban climate is the air quality. This is because the urban environment has significant interactions with air flow. Air flow and dispersion profiles near the surface of a city are different as compared to the pre-existing landscape. This is due to the differences in the budget of momentum. Alteration of land surface in terms of roughness, land uses and types of land surface cover has created the urban-induced wind circulation features (Grimmond and Oke, 1995; Arnfield, 2003), reduced the wind speed and altered the wind direction (Bridgman and Oliver, 2006; Harman and Belcher, 2006).
Bridgman and Oliver (2006) and Griffiths (1976) both suggest that roughness increases with the geometry of the buildings creating extra turbulence, but it is inversely proportional to the size and the spatial arrangement of the buildings. Interactions of the urban environment with the air flow decreases the wind speed due to surface friction and results in the increase of air pollution and atmospheric stagnation periods. However, in some cases the urban street canyon generally pronounced as channelling like wind tunnels, increases the strength of turbulence. Trees along the roadsides also play an important role in reducing wind speeds (Griffiths, 1976; Arnfield, 2003; Bridgman and Oliver, 2006).
CHAPTER 3 METHODOLOGY

3.1 Measurement site

This study focuses on one of the most densely populated cities, Greater London, the capital of England and the United Kingdom. Greater London comprises the City of London, 13 inner and 19 outer boroughs. This city is located in the South East of England on the river Thames and covers a total of 1,580 km² (Brown, 2014). It is the largest city in Europe. By 1800, the population of London had exceeded one million, and recently the Greater London Authority (GLA) produced a projection on London’s population that it would reach about 8.63 million in 2015 (Greater London Authority, 2015).

One year (2012) of precipitation forcing data with temporal resolution of 5 minute intervals from the Strand campus (KSK) site at Kings College London (51°30’N 0°7’W, elevation of 35 m) (Kotthaus and Grimmond, 2014) were used for this project. Precipitation was monitored by an automatic weather station (WXT510, Vaisala) and data was gap-filled using nearby stations, Davis Vantage Pro Plus stations from North Kensington Dartrey Tower (NDT) at Kings College London or North Kensington Grenfell Tower (NGT), if NDT data was not available to provide a continuous time series.

The SUEWS model also requires the following meteorological input variables as shown in Table 1(a), which are the mean wind speed, relative humidity, air temperature, station air pressure and incoming short wave radiation. These were provided at 5 minute resolution from nearby stations (NDT or NGT if NDT data was not available). Also, when there is zero rainfall at all gauges in the network, data was gap-filled using a zero amount.
3.2 Data processing

In order to investigate the impact of the temporal resolution of precipitation forcing data on the modelled surface energy and water balance, the 5 minute precipitation data was used to generate input files representing different temporal resolutions. Each meteorological input file has a resolution of 5 minute to match the model time step used. For example, the 5 minute precipitation time series was created by simply using the 5 minute dataset. For the 10 minute precipitation time series, the 5 minute data was first averaged to 10 minute and then each 10 minute value was divided by 2 to provide 2 identical 5 minute values. For 60 minute precipitation time series, the 5 minute data was first averaged to 60 minute and then each 60 minute value was divided by 12 to provide 12 identical 5 minute values.

The following temporal resolutions were used: 5, 10, 20, 30, 45, 60, 80, 90, 120, and 180 minute. The analysis used 5 minute rainfall data as a reference, compared to rainfall data accumulated to the various temporal resolutions indicated. It is important to bear in mind that only the precipitation forcing data was changed. As for the other meteorological input variables such as the mean win speed, relative humidity, air temperature, station air pressure and incoming short wave radiation were fixed in each case.

All the temporal resolutions used must be able to be divisible by 24 hours so that the daily total rainfall amount does not change. Thus changing the temporal resolution does not change the daily total rainfall amount. So, the analysis has the same amount of water to test the impact of temporal resolution on the surface energy and water balance. However, the temporal variation of the precipitation pattern had been altered.

Figure 3 illustrates the example of 180 minute of rainfall event redistributed for the analysis undertaken in this study to see that how the rainfall pattern changes according to the temporal resolution used. The maximum 5 minute rate for each temporal resolution is given in each sub-figure. From the comparison, notice that the
original temporal variation of rainfall pattern (Figure 3(a)) has been altered from periods of rain, no rain, light rain and intense rain to a long duration of light rain only (Figure 3(j)).

Based on Figure 3, in general, if we are interested in how precipitation has changed in its extreme, changing the temporal resolutions of precipitation forcing data will lead to a different result. For example, the maximum rainfall intensity in 5 minute for temporal resolution of 5 minute was 3.9 mm (Figure 3(a)). However, the maximum rainfall intensity in 5 minute for temporal resolution of 180 minute had decreased to 0.47 mm (Figure 3(j)). So, instead of rainfall intensity of 3.9 mm, the precipitation extreme decreased to 0.47 mm for this study.

Another significant difference seen from comparing the sub-figures between fine (e.g. 5 minute) and coarse temporal resolution (e.g. 180 minute), is the number of extreme occurrences. For example, instead of the 5 minute extreme precipitation of 3.9 mm (Figure 3(a)), 36 occurrences of 0.47 mm occur (Figure 3(j)). All these changes will impact the statistical analysis of precipitation extremes.

The SUEWS model was run at a time step of 5 minute with 10 meteorological forcing files for the 10 different temporal resolutions of precipitation data. The model was run for the central London site (Section 3.1). Table 3 shows the surface cover fraction used. The model was set to assume no extra water supply from irrigation and no snow events. Among the meteorological output (Table 1(b)), this project analyses net all-wave radiation, incoming short-wave radiation, sensible heat flux, latent heat flux, anthropogenic heat flux, storage heat flux, evapotranspiration, soil moisture deficit, runoff and state of the surface storages.
Figure 3: Example of 180 minute of rainfall event redistributed for the analysis undertaken in this study. (a) Original 5 minute temporal resolution; (b) 10 minute temporal resolution of redistributed rainfall event; (c) 20 minute temporal resolution of redistributed rainfall event; (d) 30 minute temporal resolution of redistributed rainfall event; (e) 45 minute temporal resolution of redistributed rainfall event; (f) 60 minute temporal resolution of redistributed rainfall event; (g) 80 minute temporal resolution of redistributed rainfall event; (h) 90 minute temporal resolution of redistributed rainfall event; (i) 120 minute temporal resolution of redistributed rainfall event; (j) 180 minute temporal resolution of redistributed rainfall event. Note: y-axis changes between plots but all have the same total rainfall amount. The maximum 5 minute rate is given for each temporal resolution is given.
<table>
<thead>
<tr>
<th>Variables</th>
<th>Descriptions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr_Paved</td>
<td>Surface cover fraction of paved surfaces</td>
<td>0.43</td>
</tr>
<tr>
<td>Fr_Bldgs</td>
<td>Surface cover fraction of buildings</td>
<td>0.38</td>
</tr>
<tr>
<td>Fr_DecTr</td>
<td>Surface cover fraction of deciduous trees and shrubs</td>
<td>0.02</td>
</tr>
<tr>
<td>Fr_Grass</td>
<td>Surface cover fraction of grass</td>
<td>0.03</td>
</tr>
<tr>
<td>Fr_Water</td>
<td>Surface cover fraction of open water</td>
<td>0.14</td>
</tr>
<tr>
<td>Total fraction</td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Table 3:** Surface cover fraction (Fr) used in SUEWS model. (From Kotthaus and Grimmond, 2014)
CHAPTER 4 FINDINGS AND DISCUSSION

4.1 Precipitation

For this study period (January 2012 to December 2012), there were 184 days with rain (Figure 4). The annual rainfall for 2012 was 692.34 mm with mean daily total rainfall amount of 1.89 mm. The maximum hourly rainfall intensity of 12.9 mm h\(^{-1}\) occurred on 25\(^{th}\) August 2012. This was due to the approach of a low pressure system. The UK Met Office had issued a yellow warning for the August Bank Holiday for England and Wales valid from 0005Z to 2200Z 25\(^{th}\) August 2012 (UK Met Office, 2015a; UKweatherworld, 2015).

![Time series for precipitation 2012](image)

**Figure 4:** Observed precipitation forcing data for the year 2012 in central London (see Section 3.1 for details). Maximum 1 minute rainfall rate was 1.1 mm.

Table 4 summarizes the monthly total rainfall amount and monthly maximum intensity for 2012. September had the maximum rainfall intensity of 30.3 mm day\(^{-1}\), which occurred on 23\(^{rd}\) September 2012. The wettest month was April with monthly total of 118.4 mm month\(^{-1}\).
### Table 4: Monthly totals rainfall and maximum intensity for the year 2012 as observed in central London.

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly totals [mm month$^{-1}$]</th>
<th>Maximum intensity [mm day$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>27.54</td>
<td>9.30</td>
</tr>
<tr>
<td>February</td>
<td>16.14</td>
<td>9.84</td>
</tr>
<tr>
<td>March</td>
<td>9.50</td>
<td>6.50</td>
</tr>
<tr>
<td>April</td>
<td>118.40</td>
<td>20.90</td>
</tr>
<tr>
<td>May</td>
<td>39.00</td>
<td>12.00</td>
</tr>
<tr>
<td>June</td>
<td>114.62</td>
<td>25.30</td>
</tr>
<tr>
<td>July</td>
<td>70.82</td>
<td>17.10</td>
</tr>
<tr>
<td>August</td>
<td>39.30</td>
<td>21.80</td>
</tr>
<tr>
<td>September</td>
<td>49.20</td>
<td>30.30</td>
</tr>
<tr>
<td>October</td>
<td>49.20</td>
<td>8.90</td>
</tr>
<tr>
<td>November</td>
<td>69.17</td>
<td>17.90</td>
</tr>
<tr>
<td>December</td>
<td>89.43</td>
<td>20.80</td>
</tr>
</tbody>
</table>

4.2 Urban water balance and energy balance components

This section will discuss the findings on the impact of temporal resolution of precipitation forcing data on modelled surface energy and water balance.

4.2.1 Soil Moisture Deficit

According to Met Éireann (2015), soil moisture deficit is the amount of rain needed to bring the soil moisture content back to field capacity. Soil moisture deficit is important in order to determine whether the soil is near-saturated and therefore influence the runoff and hence helps in flood forecasting. Figure 5(a) shows the soil moisture deficit for year 2012 with 10 different temporal resolutions while Figure 5(b) shows zooming on month September 2012 as an example and impact of intense rainfall on soil moisture deficit.

In general, SUEWS model is able to follow the changes in the variable soil moisture deficit for the precipitation events. As expected, the soil moisture deficit started to increase steeply when moving into the summer. However, due to the continuous
precipitation events in June with monthly total rainfall of 114.62 mm month\(^{-1}\) (Table 4), the modelled soil moisture deficit gradually decreased.

Figure 5(a) shows that the modelled soil moisture deficit for the different temporal resolutions had a similar pattern to each other. The impact of temporal resolutions started to influence the modelled output clearly from mid-May when the modelled soil moisture deficit started to deviate. A clear sharp decrease in soil moisture deficit was observed on 23\(^{rd}\) September 2012 – the day with maximum daily total rainfall amount for the year 2012. Different temporal resolution produced different modelled output in response to the precipitation events. The modelled soil moisture deficit using 180 minute temporal resolution had decreased about 20\%, from the modelled soil moisture deficit using 5 minute temporal resolution based on the maximum difference occurred in September.

As discussed in Section 2.2, urbanization is associated with decreased infiltration rates. As the temporal resolution of precipitation forcing data becomes coarser, given the same daily total rainfall amount, time taken for a rainfall event had become longer. For 5 minute temporal resolution, the intensity of precipitation is higher compared to 180 minute temporal resolution. Thus, the rate of surface runoff for 5 minute temporal resolution is expected to be higher than surface runoff for 180 minute temporal resolution. As a consequence, the infiltration rate is higher for 180 minute temporal resolution compared to 5 minute temporal resolution. This explained that as temporal resolution of precipitation forcing data increased, the soil moisture deficit decreased as illustrated in the Figure 5(a).

Looking more closely at Figure 5(b), it was found that before the intense rainfall, 90 minute temporal resolution’s output was closer to 5 minute temporal resolution’s modelled soil moisture deficit. However, after the day 23\(^{rd}\) September 2012, the 80 minute temporal resolution performed better but still both 80 minute and 90 minute temporal resolutions’ modelled soil moisture deficit are close to each other.
Figure 5: Soil moisture deficit for (a) 2012 and (b) September for the 10 temporal resolutions as modelled by SUEWS for central London. The temporal resolutions are the length of time the rainfall is averaged over (see Section 3.2 for details).
4.2.2 Evaporation

Suppose variable x represents the daily total rainfall amount. So, ratios of normalized daily total evaporation according to temporal resolutions for the whole year were plotted with 8 colour scales as shown in Table 5 below. Lines with unfilled diamonds represent one day before the maximum daily total rainfall amount, while filled diamonds represent one day after the maximum occurred in order to have a better comparison on the impact of temporal resolutions given large amounts of water input.

<table>
<thead>
<tr>
<th>Daily total rainfall amount, x [mm day⁻¹]</th>
<th>Colour</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 0</td>
<td>Red</td>
<td>No rain</td>
</tr>
<tr>
<td>0 &lt; x ≤ 0.4</td>
<td>Pink</td>
<td>1st quartile, x = 0.4 mm</td>
</tr>
<tr>
<td>0.4 &lt; x ≤ 1.8</td>
<td>Yellow</td>
<td>Median, x = 1.75 mm</td>
</tr>
<tr>
<td>1.8 &lt; x ≤ 4.6</td>
<td>Green</td>
<td>3rd quartile, x = 4.565 mm</td>
</tr>
<tr>
<td>4.6 &lt; x ≤ 10</td>
<td>Aqua</td>
<td></td>
</tr>
<tr>
<td>10 &lt; x ≤ 20</td>
<td>Blue</td>
<td></td>
</tr>
<tr>
<td>20 &lt; x &lt; max</td>
<td>Purple</td>
<td></td>
</tr>
<tr>
<td>x = max</td>
<td>Black</td>
<td>x maximum = 30.3 mm</td>
</tr>
</tbody>
</table>

Table 5: Colour scale used in ratio plots.

The normalized daily total evaporation ratio was obtained using:

\[
\text{Normalized daily total evaporation ratio} = \frac{\text{Daily total evaporation}_{i}}{\text{Daily total evaporation}_{5}}
\]

Where \(i\) = temporal resolutions of 5, 10, 20, 30, 45, 60, 80, 90, 120, 180 minutes.

In order for better comparison, the comparisons were discussed in terms of percentage for the following discussions. The percentages were obtained using:

\[
\text{Difference in percentage} = \left(1 - \frac{\text{Maximum difference in daily total evaporation}_{i}}{\text{Daily total evaporation}_{5}}\right) \times 100\%
\]

Where \(i\) = temporal resolutions of 5, 10, 20, 30, 45, 60, 80, 90, 120, 180 minutes.
Results were plotted as normalized daily total evaporation ratios shown in Figure 6. Figure 6 illustrates that daily total evaporation predicted by SUEWS increased as the temporal resolution of precipitation forcing data decreased. However, not every day gave the same results. An obvious decrease (evaporation ratios less than 1) occurred when the daily total rainfall amount was less than or equal to 0.4 mm (pink lines in Figure 6). For these days (pink lines), given that the daily total rainfall amount was less than or equal to 0.4 mm, the only possible maximum rainfall intensity would be 0.4 mm h$^{-1}$. As the temporal resolution of precipitation forcing data decreased, the maximum rainfall intensity also decreased, in this case, less than 0.4 mm h$^{-1}$. For 5 minute temporal resolution, higher rainfall intensity, more water will act as surface runoff which leads to a decrease in evaporation as well as lesser amount of water available to infiltrate into the soil. As for 180 minute temporal resolution of precipitation forcing data, the rainfall intensity is not as much as 5 minute temporal resolution’s rainfall intensity. Due to lesser amount of available water input at a time, the amount of water available as evaporation has to be decreased in the water balance cycle.

The rainfall intensity is reduced as the temporal resolution of precipitation forcing data is decreased (as illustrated in Figure 3) which leads to a smaller amount of water on the surface available to evaporate. Although 23$^{rd}$ September 2012 was the day with maximum daily total rainfall amount of 30.3 mm (black line with pentagon marker), but the evaporation ratio did not increase as much as compared to those days where the daily total rainfall amount was more than the 3$^{rd}$ quartile, $x = 4.565$ mm.

All days are plotted and selected days for month May, August and September will be discussed in more detail to see the variation of daily precipitation distribution, modelled surface energy and water balance throughout the day. For the other months, the normalized daily total evaporation against 10 different temporal resolutions plots are included in Appendix A.
Figure 6: Comparison of normalized daily total evaporation against 10 temporal resolutions. Note: Unfilled diamonds represent the day before $x=\text{max}$; Filled diamonds represent the day after $x=\text{max}$; Black filled pentagons represent $x=\text{max}$. (see Table 5 for further information).

Figure 7 shows the plot in May for normalized daily total evaporation against 10 temporal resolutions. In general, the daily total rainfall amount more than median but less than maximum has more impact on the daily total evaporation. Days with no rain generally showed no significant impact by changing the temporal resolution of precipitation forcing data. 15th May 2012 (as indicated in the plot) showed a decrease of about 2% of evaporation at 10 and 20 temporal resolutions but increased after temporal resolutions of 20 minute. The percentage was calculated using maximum difference compared to the reference rainfall data as shown in the equation 5. Investigation was carried out to see the variation of meteorological conditions throughout the day and the reasons were examined which caused the decrease in daily total evaporation using 20 minute temporal resolution but increase in daily total evaporation using 180 minute temporal resolution.

Figure 8 – 10 shows the time series on 15th May 2012 to compare the modelled output using 5, 20, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes.
Figure 7: Comparison for May normalized daily total evaporation against 10 temporal resolutions. Note: Unfilled diamonds represent the day before x=max; Filled diamonds represent the day after x=max; Black filled pentagons represent x=max. (see Table 5 for further information).

15th May 2012 was a day with daily total rainfall amount of 10.2 mm. From the observation, it was noticed that the surface state of grass is always the wettest as compared to other surface states. It was observed that with two hours of rain from 0600 to 0800 (Figure 8(a), Figure 9(a)), the surface states were able to stay in wet condition for another 4 hours after the rainfall until 1200. However, the modelled surface state for grass was able to stay longer (Figure 10(a)) for another two hours due to longer rainfall duration.

Although there was a rain with 0.1 mm around 1300, it was able to influence the evaporation and hence result in an increase (Figure 8(a), Figure 9(a)). As the temporal resolution decreased, the impact from this 0.1 mm of rainfall at the modelled output was not seen (Figure 10(a)). The daily total evaporation for 20 minute temporal resolution decreased because the rainfall duration was still following the rainfall duration for 5 minute temporal resolution. However, the rainfall intensity had decreased from maximum of 3.0 mm to 0.9 mm which means the same time period but lower rainfall intensity for 20 minute temporal resolution. While for 180 minute temporal resolution, although the rainfall intensity had decreased too, but due to
longer duration of rainfall, the continuous supply of water from rainfall managed to continue the evaporation process and hence, was able to sustain a higher daily total evaporation compared to 20 minute temporal resolution. Thus, the daily total evaporation had decreased at 20 minute temporal resolution but increased after that.

According to Järvi et al. (2011), latent heat flux depends on the surface wetness states while sensible heat flux is calculated as residual from the hourly available energy minus the hourly latent heat flux. Also, evaporation process makes the link between the water balance and energy balance. As the evaporation increases, more energy will be needed and hence the latent heat of vaporization increases. So, amount of energy available as sensible heat reduces. From these energy component plots (Figure 8(b), Figure 9(b), Figure 10(b)), as expected, the latent heat flux is following the pattern of evaporation. Due to the changes in the daily total evaporation as temporal resolution of precipitation forcing data decreases, the energy partitioning between latent heat flux and sensible heat flux will change accordingly. Thus, observed peak in latent heat flux results in the opposite peak for sensible heat flux as shown in the figures.
Figure 8: Meteorological conditions on 15th May 2012 using 5 minute temporal resolution of precipitation forcing data. (a) Observed 24 hours rainfall, ‘Tot.Pi’ represents the daily total rainfall amount; (b) Modelled evaporation, Tot.Ei’ represents the daily total evaporation; (c) Modelled runoff, ‘Tot.Roi’ represents the daily total runoff; (d) Modelled surface states, ‘NWSti’ represents land surface state with water surface excluded, ‘St_Paved’ represents state of paved surface, ‘St_Bldgs’ represents state of building surface, ‘St_EveTr’ represents state of evergreen surface, ‘St_DecTr’ represents state of deciduous surface, ‘St_Grass’ represents state of grass surface, and ‘St_BSoil’ represents state of bare soil surface; (e) Modelled available energy components, ‘qe’ represents latent heat flux, ‘qn’ represents net all-wave radiation, ‘qh’ represents sensible heat flux, and ‘qf’ represents anthropogenic heat flux.

Figure 9: Meteorological conditions on 15th May 2012 using 20 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Figure 10: Meteorological conditions on 15th May 2012 using 180 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

For August (Figure 11), the evaporation increased about 45% as the temporal resolution decreased under a wet condition which was the day 25th August 2012 (as indicated in the plot). The percentage was calculated using equation 5 with $i = 180$ minute temporal resolution modelled evaporation. As mentioned in section 4.1, this was the day that had the maximum hourly rainfall intensity of 12.9 mm h$^{-1}$ for year 2012. However, if looking at whole year time frame, maximum intensity of hourly rainfall amount does not appear to be the dominant factor that impacts on evaporation.

Figure 12 – 14 shows the time series on 25th August 2012 to compare the modelled output and to investigate the variation of meteorological conditions throughout the day using 5, 60, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes.
25th August 2012 was a day with daily total rainfall amount of 21.8 mm. Figure 12(a), Figure 13(a) and Figure 14(a) shows the wet conditions in land surface states in the morning suggesting that water supply was available there for the evaporation process although there was no rain in the morning. Before the rainfall occurred, the available water had decreased to zero as the available net all-wave radiation increased at 0800 (Figure 12(b), Figure 13(b), Figure 14(b)). The energy components which started to increase might be due to the sunrise. According to HM Nautical Almanac Office (2015), sunrise in London for mid-August occurs at 0545BST. Incoming solar radiation results more available source of energy, hence increases the evaporation process.

Observed rainfall started after about 1300 (Figure 12(a), Figure 13(a)) but started at 1200 (Figure 14(a)) as the temporal resolution of precipitation forcing data decreased. Due to the rainfall distribution, the land surface states were able to maintain their wet conditions until the late night especially for 180 minute temporal resolution of precipitation forcing data. So, depending on the rainfall distribution, as
the temporal resolution of precipitation forcing data decreased, the daily total evaporation increased regardless of the decrease in rainfall intensity for this day. The variation of latent heat flux throughout the day is following the variation of evaporation. As the temporal resolution of precipitation decreased, the latent heat and sensible heat fluxes throughout the day have seen changes from many fluctuations into only one sharp increase following the evaporation pattern.

Figure 13(a) shows that there was some unrealistic behaviour on the modelled output on daily total runoff (Tot.Roi), land surface state (NWSti), state of paved surface (St_paved) and state of building surface (St_bldgs). This might be due to the model setting on how the variables react to each other or sensitivity of each variable in each time step. This reveals that further improvement is needed for SUEWS model.

Figure 12: Meteorological conditions on 25th August 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Figure 13: Meteorological conditions on 25th August 2012 using 60 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Another special situation observed from the monthly plot for August (Figure 11) was for case of no rain after 25th August 2012, which was 26th August 2012 (as indicated in the plot). The normalized daily total evaporation ratio obtained was not equal to 1. Evaporation for 26th August 2012 showed an obvious steady increase of about 7% as the temporal resolution decreased on this no rain day. The percentage was calculated using equation 5 with i = 180 minute temporal resolution modelled evaporation.

Figure 15 – 17 show the time series on 26th August 2012 to compare the modelled output and to investigate the variation of meteorological conditions throughout the day using 5, 60, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes. It is evident that due to the contribution and remaining sources of water input from 25th August 2012 (Figure 15(a) and Figure 16(a)), the land surface states were able to maintain at wet condition early in the morning of 26th August 2012. As the temporal resolution decreased, the amount of water at the land surface states has increased (Figure 17(a)) resulting in more available sources of water for the evaporation process. Thus, as temporal resolution of precipitation forcing data decreased, the daily total evaporation increased.

For this day, both the net all-wave radiation and sensible heat flux followed each other. Figure 15(e), Figure 16(e) and Figure 17(e) show negative values of net all-wave radiation for 26th August 2012 suggesting that low values of energy causing
smaller amount of available energy were used in evaporation processes. Thus the latent heat flux is lower than the sensible heat flux. However, as the temporal resolution of precipitation forcing data decreased, the latent heat flux increased which is in line with the results of increased daily total evaporation.

**Figure 15:** Meteorological conditions on 26th August 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Figure 16: Meteorological conditions on 26\textsuperscript{th} August 2012 using 60 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

180 min resolution
Figure 17: Meteorological conditions on 26\textsuperscript{th} August 2012 using 180 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

Figure 18 shows the plot in September for normalized daily total evaporation against 10 temporal resolutions. As mentioned in section 4.1, September was the month with maximum daily total rainfall amount of 30.3 mm day\textsuperscript{−}\textsuperscript{1} which occurred on 23\textsuperscript{rd} September 2012 (as indicated in the plot). As discussed in earlier part, the daily total evaporation ratio does not increase as much as those days with daily total rainfall amount more than the 3\textsuperscript{rd} quartile, x = 4.565 mm. The green line, 12\textsuperscript{th} September 2012 (as indicated in the plot) showed an unusual increase in pattern of evaporation for about 33\% compared to other days in September. The percentage was calculated using equation 5 with i = 180 minute temporal resolution modelled evaporation. Also, this day showed a decrease at 20 minute temporal resolution.

Figure 18: Comparison for September normalized daily total evaporation against 10 temporal resolutions. Note: Unfilled diamonds represent the day before x=max; Filled diamonds represent the day after x=max; Black filled pentagons represent x=max. (see Table 5 for further information).
Further investigations were carried out in order to determine which of the meteorological conditions were causing an impact for 12th September 2012 on the daily total evaporation. The following detail plots (Figure 19 – 21) were used to see the time series on 12th September 2012 using 5, 20, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes.

For this day, the modelled daily total evaporation behaved similar to 15th May 2012 as discussed earlier. Looking at 5 minute temporal resolution rainfall distribution (Figure 19(a)), the rainfall occurred between 1900 and 2000. Timing of the rainfall was the reason that the modelled daily total evaporation ratio showed decreased and increased alternately as the temporal resolution of precipitation forcing data decreased. For example, for temporal resolution of 60 minutes the rainfall amount was still at the one hour time period: 1900 – 2000. While for 90 minutes temporal resolution, the rainfall amount had been divided into small amount into two time periods: 1800 – 1930 and 1930 – 2100.

With the same duration of rainfall, the maximum 5 minute rainfall intensity had decreased from 1.5 mm (Figure 19(a)) to 0.7 mm (Figure 20(a)). Thus, the modelled daily total evaporation for 20 minute temporal resolution decreased due to the lower intensity of rainfall but for the same rainfall duration. However, as the temporal resolution of precipitation forcing data decreased to 180 minute temporal resolution, the rainfall duration increased (Figure 21(a)). Although there was a decrease in rainfall intensity at 20 minute temporal resolution modelled evaporation, but the long duration of rainfall managed to sustain the evaporation for longer duration and hence resulting in a higher evaporation rate.

Due to the change in evaporation process, the latent heat and sensible heat fluxes responded accordingly. As the temporal resolution decreased, the small variations in these fluxes throughout the day had becomes inconspicuous (Figure 19(b), Figure 20(b), Figure 21(b)).
Figure 20(a) shows that there was some unrealistic behaviour on the modelled output similar to the modelled output for the day of 25\textsuperscript{th} August 2012. Closer look into the details of the SUEWS model physics is needed for the improvement.

Figure 19: Meteorological conditions on 12\textsuperscript{th} September 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
**Figure 20**: Meteorological conditions on 12th September 2012 using 20 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Figure 21: Meteorological conditions on 12th September 2012 using 180 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

Another important findings on the impacts of temporal resolution of precipitation forcing data was that for less rain situation, daily total rainfall amount less than or equal to 0.4 mm (pink lines in Figure 6), generally showed a decrease in the modelled evaporation as the temporal resolution decreased. Example date chosen for further investigations was 25th September 2012 (as indicated in Figure 18) where it showed the largest decline of about 3.3% in year 2012 at 120 minute temporal resolution. The percentage was calculated using equation 5 with \( i = 120 \) minute temporal resolution modelled evaporation.

Figure 22 – 24 show the time series on 25th September using 5, 120, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes. As discussed earlier in this section, the decrease in the modelled evaporation was related to the rainfall time period and duration. For this day, the decrease in modelled evaporation (Figure 23(a)) was due to the decrease in rainfall intensity but still occurred with the same rainfall time period (Figure 22(a)).

Peak of the net all-wave energy resulted in the sharp increase in evaporation due to the high amount of available energy (Figure 22(b), Figure 23(b) and Figure 24(b)). In addition, the rainfall also occurred in the midday. This rainfall contributed to the sharp increase in evaporation at the midday. However, these light rains did not lead to the condition of wet surface states for a long time. The surface states decreased and dropped to zero after around two hours of rain stop time period. Another
rainfall event occurred in the late night. However, due to insufficient of available net all-wave radiation, the evaporation did not increase as high as compared to the midday evaporation.

So far this section has focussed on the impacts of temporal resolution of precipitation forcing data on the modelled evaporation. The following section will discuss on the impacts of temporal resolution of precipitation forcing data on the modelled runoff.

![5 min resolution](image)

**Figure 22:** Meteorological conditions on 25th September 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
**Figure 23:** Meteorological conditions on 25th September 2012 using 120 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
4.2.3 Runoff

The same colour scale was applied for runoff analysis. Ratios of normalized daily total runoff according to temporal resolutions for the whole year were plotted as shown in Figure 25.

Considering that there were situations in which the runoff values were equal to zero, a constant figure of 100 was added to the output runoff obtained before proceeding for the normalized daily total runoff ratio calculations. This was done to avoid errors associated with divisions involving values of zero (0) in equation 6 [6] below. The normalized daily total runoff ratio was obtained using:

\[
\text{Normalized daily total runoff ratio} = \frac{\text{Daily total runoff}_i}{\text{Daily total runoff}_5}
\]  \[6\]

Where \(i\) = temporal resolutions of 5, 10, 20, 30, 45, 60, 80, 90, 120, 180 minutes.

In order for a better comparison, the comparisons were discussed in terms of percentage for the following discussions. The percentages were obtained using:

\[
\text{Difference in percentage} = \left(1 - \frac{\text{Maximum difference in daily total runoff}_i}{\text{Daily total runoff}_5}\right) \times 100%
\]  \[7\]

Where \(i\) = temporal resolutions of 5, 10, 20, 30, 45, 60, 80, 90, 120, 180 minutes.
Figure 25 shows that generally for most of the cases, daily total runoff decreased as the temporal resolution decreased. However, there were some exceptional cases shown in the plot. A decrease in runoff as expected was seen due to the increase in evaporation as the temporal resolution decreased (Section 4.2.2). This is because for the same amount of daily total rainfall, bigger amount had gone as evaporation and hence lesser amount of available water gone as runoff in order to achieve the surface water balance. Or in other words, decreasing runoff leads to the increased evaporation in the water balance budget.

Selected days for month February, April and December will be discussed in more detail to see the variation of daily precipitation distribution, modelled surface energy and water balance throughout the day. For the other months which were not discussed, the normalized daily total runoff against 10 temporal resolutions plots were included in Appendix B.

Figure 26 shows the plot in February for normalized daily total runoff against 10 temporal resolutions. 6th February (as indicated in the plot) was the day with no rain, but the modelled runoff showed an increase of about 0.1% runoff after 90 minute
temporal resolution. The percentage was calculated using equation 7 with i = 180 minute temporal resolution modelled runoff. Further investigations were carried out in order to determine which of the meteorological conditions caused an increase on the daily total runoff for this day.

![Figure 26: Comparison for February normalized daily total runoff against 10 temporal resolutions. Note: Unfilled diamonds represent the day before x=max; Filled diamonds represent the day after x=max; Black filled pentagons represent x=max. (see Table 5 for further information).](image)

Figure 27 - 29 show the time series on 6th February 2012 using 5, 120, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes.

6th February was same as 26th August which was not a raining day but changes in temporal resolution of precipitation forcing data lead to changes in modelled output. Both days were not a raining day. However, there were sources of water available from the surface states (Figure 27(a), Figure 28(a), and Figure 29(a)). For 6th February, it was lesser amount of evaporation compared to 26th August. This is because 6th February has lower value of available energy (Figure 27(b), Figure 28(b), and Figure 29(b)) which resulted in fewer amounts of evaporation processes. This explains why the runoff and surface states showed a gradually decrease instead of sharp decrease.
As the temporal resolution decreased, the amount of water in the surface states increased. In order to achieve surface water balance, these extra amounts of water has to go as a runoff. Moreover, there was low value in the net all-wave radiation which implies a cloudy condition for 6th February, so, lesser amount of available energy for the evaporation process. Hence, as the temporal resolution of precipitation forcing data decreased, the daily total runoff increased.

Figure 27: Meteorological conditions on 6th February 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Figure 28: Meteorological conditions on 6\textsuperscript{th} February 2012 using 120 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

120 min resolution

180 min resolution
Figure 29: Meteorological conditions on 6th February 2012 using 180 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

Figure 30 shows the plot in April for normalized daily total runoff against 10 temporal resolutions. For April, there was an increase of 0.3% runoff ratio for day 30th April 2012 (as indicated in the plot) as the temporal resolution decreased. The percentage was calculated using equation 7 with i = 120 minute temporal resolution modelled runoff. Notice that the plot for May (shown in Appendix B) has a total of 32 days. This is because the maximum rainfall intensity for May occurred at the 1st May, so the previous day (30th April 2012) was plotted in both figures.

Figure 30: Comparison for April normalized daily total runoff against 10 temporal resolutions. Note: Unfilled diamonds represent the day before x=max; Filled diamonds represent the day after x=max; Black filled pentagons represent x=max. (see Table 5 for further information).
Figure 31 – 33 show the time series on 30\textsuperscript{th} April 2012 using 5, 60, and 180 minute temporal resolutions of precipitation forcing data to illustrate the variation of meteorological conditions throughout the day. These three plots used the same y-scale for better comparison purposes.

30\textsuperscript{th} April was a day after the maximum daily total rainfall occurred for April with daily total rainfall amount of 1.6 mm. However, looking at the low values of surface states (Figure 31(a), Figure 32(a), and Figure 33(a)) at early morning indicated that the source of water from 29\textsuperscript{th} April did not stay at the surface states for a long time on 30\textsuperscript{th} April. High evaporation process at noon leads to the grass surface and evergreen surface turns into dry condition.

Because of the rainfall distribution pattern, as the temporal resolution of precipitation forcing data decreased, the surface runoff increased. Moreover, the rainfall intensity is evenly distributed between the 2000 and 2200. In addition, the peak rainfall, 0.5 mm, had been spread into longer duration. Although this rainfall intensity decreased as the temporal resolution decreased, but the amount of water was still higher as compared to the 0.1 mm rainfall. So, as the temporal resolution decreased, the runoff increased due to the longer duration of rainfall.

From the results, observed increases in evaporation might be due to the high amount of net all-wave radiation (Figure 31(b), Figure 32(b), and Figure 33(b)) which provide sufficient energy for the evaporation processes. So, despite the surface runoff increased, the evaporation also increased due to high values of energy.
**Figure 31:** Meteorological conditions on 30<sup>th</sup> April 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
**Figure 32:** Meteorological conditions on 30th April 2012 using 60 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

**Figure 33:** Meteorological conditions on 30th April 2012 using 180 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Another situation chosen is 3rd April 2012 (as indicated in the plot). It was a day after a continuous of 16 days of no rain day since 17th March 2012 and then the first occurrences of rainfall with daily total rainfall amount of 5.8 mm were observed. It was the longest dry spell for year of 2012. Figure 34 – 36 show the time series on 3rd April 2012 to compare the modelled output using 5, 60, and 180 minute temporal resolutions of precipitation forcing data. These three plots used the same y-scale for better comparison purposes.

The rain started in the afternoon and dry conditions were observed on the surface states (Figure 34(a), Figure 35(a), and Figure 36(a)) at the starting of the day. As soon as the rainfall occurred, the surface states water content increased. As the rain intensity increased, the runoff increased considering that the amount of water in surface states had increased. Higher runoff was observed due to the higher values of land surface states. Later at about time 2000, even with smaller amount of rainfall resulted in higher values of surface states as compared to time 1800 due to the accumulation of available water. Moreover, due to the rainfall distribution pattern throughout the day, as the temporal resolution of precipitation forcing data decreased, the duration of rainfall had increased. The continuous water supply led to the increase in surface runoff.

The temporal resolution of precipitation forcing data also affects the modelled surface energy balance. Figure 34(b), Figure 35(b), and Figure 36(b) show that the variation of latent heat and sensible heat fluxes has become smoother as the temporal resolution of precipitation forcing data decreased. Variation throughout the day has become hidden by using a coarse input data.
Figure 34: Meteorological conditions on 3rd April 2012 using 5 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
Figure 35: Meteorological conditions on 3\textsuperscript{rd} April 2012 using 60 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).

Figure 36: Meteorological conditions on 3\textsuperscript{rd} April 2012 using 180 minute temporal resolution of precipitation forcing data. (see Figure 8 for details).
4.3 Summary of findings and discussions

Precipitation plays an important role in surface water balance. Variations in the distribution of precipitation, such as shifting from greater to lesser intensity of each individual storm, or changing in length and frequency of rainfall throughout the day, will impact the surface water balance. Thus, further knowledge of precipitation distribution can help to improve model predictions.

The study was carried out to assess the impact of temporal resolution of precipitation forcing data on modelled surface energy and water balance using available data from site Strand campus in Kings College London. The results suggest that as the temporal resolution of precipitation forcing data decreased, it resulted in a significant impact on the modelled output subject to the timing of rainfall occurrences, rainfall intensity and the rainfall duration.

In general, results showing that with daily total rainfall amount more than median but less than maximum have more impacts on the modelled surface energy balance and water balance. As the temporal resolution of precipitation forcing data decreased, the modelled evaporation increased while modelled runoff also decrease. Changes in evaporation led to changes in latent heat and sensible heat fluxes.

However, for days with daily total rainfall amount less than 0.4 mm, 1st quartile for this project, changes in temporal resolution of precipitation forcing data resulted in an opposite impacts on modelled evaporation. So as the temporal resolution of precipitation forcing data decreased, the modelled evaporation decreased.

For days with no rain, the impacts of temporal resolution were less significant due to the differences in surface states and soil moisture that depend on the resolution of precipitation forcing data.
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The urban environment has a major influence on local and regional climate. Moreover, urbanization keeps increasing rapidly which leads to the increase in magnitude of urban effects. As a consequence, urban areas’ uses of resources and emissions have increased. These situations are creating more and more urban environment problems, such as the water management issues, thermal changes and poor air quality, which are mainly due to urban climates. Thus, with current urban climate understanding, further investigation and research will be needed and are vital for better adaptation and mitigation planning, energy and water balance prediction for a better future.

As discussed in the literature review (Section 2.2), there were vast research and findings found on the impacts of spatial resolution of precipitation forcing data as input for hydrological model and urban model. This research study however, focuses on the impact of temporal variation of precipitation forcing data on modelled surface urban energy and water balance. The 5 minute temporal resolution of precipitation forcing data has been used as reference rainfall data for the investigation using SUEWS model in this study.

Based on the findings and discussions, the modelled outputs clearly showed that as the temporal resolution decreased, the rainfall intensity reduced, altering the modelled evaporation, runoff as well as other variables such as the turbulent heat fluxes. By changing the temporal resolution of precipitation forcing data, it resulted in significant impacts on the modelled surface energy balance and water balance and these significant impacts were closely related to the timing of rainfall occurrences, rainfall intensity and the rainfall duration.
In general, if looking at whole year time frame, maximum intensity of hourly rainfall amount does not appear to be the dominant factor that impacts on evaporation. For days with daily total rainfall amount more than median but less than maximum has more impact on the modelled surface energy balance and water balance. The results showed that as the temporal resolution of precipitation forcing data decrease, the modelled evaporation increases with maximum of 45%, modelled runoff decreases with maximum of 0.3% and modelled soil moisture deficit decreases with maximum of 20% compared to the reference modelled output. Since evaporation process makes the link between the energy balance and water balance, changes in evaporation hence lead to changes in both latent heat and sensible heat fluxes.

However, the results show opposite impacts on modelled evaporation for days with daily total rainfall amount less than 0.4 mm, 1st quartile for this project. Consequently, as the temporal resolution of precipitation forcing data decreases, the modelled evaporation decreases with maximum of 3.3% compared to the reference modelled evaporation. As for days with no rain, the impacts of temporal resolution are less pronounced due to the differences in surface states and soil moisture that depend on the resolution of precipitation forcing data.

It can be seen that despite the no rain situation, all 180 minute temporal resolution modelled outputs were diverged significantly from the reference rainfall. Hence, the 180 minute re-analysis precipitation forcing data is not suitable to be used for the model as the rainfall is assumed to be equally distributed over this 180 minute period of time.

In conclusion, finer temporal resolution of precipitation forcing data is needed for better modelled outputs.
5.2 Recommendations

Further studies regarding the impacts of temporal resolution of precipitation forcing data using statistical analysis methods or any simple error scores such as bias, mean squared error (MSE) or root mean squared error (RMSE) would be worthwhile and more representative in terms of the significant differences.

This research has thrown up some other questions needed for further investigation. Due to the limited research time constraint, more investigation could have been carried out such as counting the frequency of intensity for the precipitation to investigate the impact of precipitation extremes. Moreover, it would be interesting to compare the modelled evaporation with eddy covariance measurements of the fluxes.

It is suggested that the same analysis could be carried out with different model time step to investigate the impacts of model temporal resolution on modelled output, for example, a model time step of 60 minute. Further investigation and experimentation on different site or area with different land surface cover such as more vegetation is recommended.

Considering that the availability of remotely sensed estimates of precipitation measurement are in the temporal resolution of 180 minute, more investigation could be done by looking at the general rainfall pattern in the area of study in order to make the modelled output more reliable. Then, instead of using the evenly distributed precipitation method, the precipitation could be divided into a Gaussian distribution rainfall pattern or a skew normal distribution rainfall pattern.
References


Appendix A

Normalized January 2012 daily total evaporation

Normalized February 2012 daily total evaporation

Normalized March 2012 daily total evaporation
Figure 37: Monthly plots for normalized daily total evaporation against 10 temporal resolutions. Note: Unfilled diamonds represent the day before x=max; Filled diamonds represent the day after x=max; Black filled pentagons represent x=max. (see Table 5 for further information).
Appendix B

(a) Normalized January 2012 daily total runoff

(b) Normalized March 2012 daily total runoff

(c) Normalized May 2012 daily total runoff
Figure 38: Monthly plots for normalized daily total runoff against 10 temporal resolutions. Note: Unfilled diamonds represent the day before \( x = \text{max} \); Filled diamonds represent the day after \( x = \text{max} \); Black filled pentagons represent \( x = \text{max} \). (see Table 5 for further information).