Pixel based sensible (QH) and latent (QE) heat fluxes
Deliverable D6.1

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1 INTRODUCTION

1.1 Purpose of the document
This document is the Deliverable 6.1 of the URBANFLUXES (URBan ANthropogenic heat FLUX from Earth observation Satellites) Project. It contains the progress on the estimation of sensible and latent heat flux $Q_E$ and $Q_H$ on a pixel base within WP6. Methods are explained and then applied to the case study of Basel. The application to London and Heraklion will be included in deliverable D6.2 by M18 when the required data are available. It also includes an overview of the URBANFLUXES project as a whole.

1.2 Definitions and acronyms

Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM</td>
<td>Aerodynamic Resistance Method</td>
</tr>
<tr>
<td>CoP</td>
<td>Community of Practice</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DSM</td>
<td>Digital Surface Model</td>
</tr>
<tr>
<td>DSS</td>
<td>Decision Support System</td>
</tr>
<tr>
<td>EO</td>
<td>Earth Observation</td>
</tr>
<tr>
<td>EC</td>
<td>Eddy Covariance</td>
</tr>
<tr>
<td>FAI</td>
<td>Frontal Area Index</td>
</tr>
<tr>
<td>LCZ</td>
<td>Local Climate Zones</td>
</tr>
<tr>
<td>LHA</td>
<td>Lufthygiene Amt (Service for air pollution)</td>
</tr>
<tr>
<td>LST</td>
<td>Land Surface Temperature</td>
</tr>
<tr>
<td>LULC</td>
<td>Land Use / Land Cover</td>
</tr>
<tr>
<td>MB</td>
<td>Management Board</td>
</tr>
<tr>
<td>MOST</td>
<td>Monin-Obukhov Similarity Theory</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetic Active Radiation</td>
</tr>
<tr>
<td>PAI</td>
<td>Plan Area Index</td>
</tr>
<tr>
<td>UEB</td>
<td>Urban Energy Budget</td>
</tr>
<tr>
<td>UMEP</td>
<td>Urban Multi-scale Environmental Predictor</td>
</tr>
<tr>
<td>URBANFLUXES</td>
<td>URBan ANthropogenic heat FLUX from Earth obser</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
</tbody>
</table>

1.3 Document references

[R1] URBANFLUXES Grant Agreement, n. 637519, 2/11/2014

[R2] URBANFLUXES Deliverable D.3.1 Urban Surface morphology land cover/use and characteristics, DEC 2015

[R3] URBANFLUXES Deliverable D.3.2.1 Preliminary LCZ classification, DEC 2015

2 PROJECT OVERVIEW

The anthropogenic heat flux ($Q_F$) is the heat flux resulting from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people. Both urban planning and Earth system science communities need spatially disaggregated $Q_F$ data, at local (neighbourhood, or areas larger than the order of 100 m x 100 m) and city scales. Such information is practically impossible to derive by point in-situ fluxes measurements, while satellite remote sensing is a valuable tool for estimating Urban Energy Budget (UEB) parameters exploiting Earth Observation (EO) data. While the estimation of $Q_F$ spatial patterns by current EO systems is a scientific challenge, the major challenge lies on the innovative exploitation of the Copernicus Sentinels synergistic observations to estimate the spatiotemporal patterns of $Q_F$ and all other UEB fluxes.

The main goal of URBANFLUXES is to investigate the potential of EO to retrieve $Q_F$, supported by simple meteorological measurements. The main research question addresses whether EO is able to provide reliable estimates of $Q_F$ for the time of the satellite acquisition. URBANFLUXES answers this question by investigating the potential of EO to retrieve $Q_F$ spatial patterns, by developing a method capable of deriving $Q_F$ from current and future EO systems. URBANFLUXES aims to develop an EO-based methodology easily transferable to any urban area and capable of providing $Q_F$ benchmark data for different applications. URBANFLUXES is expected to increase the value of EO data for scientific analyses and future emerging applications (such as urban planning and local/regional level climate change mitigation/adaptation), by exploiting the improved data quality, coverage and revisit times of the Copernicus Sentinels data. To this end, the specific objectives of the project are:

- to improve the accuracy of the radiation balance spatial distribution calculation;
- to develop EO-based methods to estimate the flux of heat storage in the urban fabric, as well as the turbulent sensible and latent heat fluxes at local scale;
- to employ energy budget closure to estimate the anthropogenic heat flux patterns;
- to specify and analyse the uncertainties associated with the derived products;
- to evaluate the products by comparisons with $Q_F$ estimations by independent methods;
- to improve the understanding of the impact of $Q_F$ on urban climate; and to communicate this understanding to the urban planning community, which will in turn lead to a better understanding of what new knowledge is needed on the ground;
- to exploit Sentinels 2 and 3 synergistic observations to retrieve UEB fluxes at the local scale, with the frequency of the Sentinel 3 series acquisitions.
- to standardise the resulting products, and by organizing an effective dissemination mechanism, to enhance their use by urban planners and decision makers in cities, as well as by EO scientists, Earth system modellers and urban climatologists.
The duration of URBANFLUXES is three years and it is divided into two main phases: during the 1st Phase an analysis method is being developed to estimate $Q_F$ spatial patterns using currently available satellite data; during the 2nd Phase the developed method will be adapted to Sentinels synergy to derive $Q_F$ spatiotemporal patterns. Three different urban areas are selected in URBANFLUXES as case studies: a highly urbanized mega city (London); a typical central European medium size city, that requires a substantial amount of energy for heating (Basel); and a smaller, low latitude Mediterranean city that requires a substantial amount of energy for cooling (Heraklion). The project uses a Community of Practice (CoP) approach, which means that in the case studies, local stakeholders and scientists meet on a regular basis to learn from each other and to make clear what aspects are important for the future users of the URBANFLUXES products.

URBANFLUXES is expected to generate a novel analysis method for estimation of UEB components from Copernicus data, enabling its integration into applications and operational services; for example to: develop rules of thumb for density and green space ratio, distinguish between insulated and non-insulated buildings and evaluate the implementation of climate change mitigation technologies, such as solar-screening and green-belting.

Despite its local importance, $Q_F$ is omitted from climate models simulations. Observations of global temperature evolution indicate a pronounced warming over the last 150 years, with an increase in the occurrence of heat waves. The added value and benefit expected to emerge from URBANFLUXES is therefore related to quality of life, because it is expected to improve our understanding of the contribution of $Q_F$ to heat wave intensity and thus to allow insight into strategies for mitigation. $Q_F$ estimates are needed for all cities to be able to document the magnitude of the fluxes effects on urban climate so that the impact of $Q_F$ can be included in climate modelling. URBANFLUXES is therefore expected to advance the current knowledge of the impacts of $Q_F$ on urban heat island and hence on urban climate, and consequently on energy consumption in cities. This will lead to the development of tools and strategies to mitigate these effects, improving thermal comfort (social benefit) and energy efficiency (economic benefit). The long term operation of the Sentinels series guarantees the future supply of satellite observations, providing the means for the development and realization of the URBANFLUXES methodology.

URBANFLUXES is expected to support sustainable planning strategies relevant to climate change mitigation and adaptation in cities, because knowledge of $Q_F$ spatio-temporal patterns is important for urban planning (e.g. to reduce or prevent $Q_F$ hot spots), health (e.g. to estimate the impact on thermal comfort) and future proofing (e.g. to plan and implement interventions towards $Q_F$ reduction in these areas). Planning tools, such as Urban Climatic Maps and Climatope Maps, should be enriched with information on $Q_F$ patterns. Mapping provides visualization of assessments of these phenomena to help planners, developers and policy makers make better decisions on mitigation and adaptation.
3 ESTIMATION OF SENSIBLE AND LATENT HEAT FLUX ON A PIXEL BASIS

3.1 Concept and approach
The turbulent heat fluxes of sensible $Q_H$ and latent $Q_E$ heat are strongly modified by the properties of the urban surface, i.e. 3D geometry, high roughness, impervious surfaces, complex source/sink distribution and injections of heat and water into the urban atmosphere by human activities (traffic, heating, waste management, etc.). The spatial variability of urban terrain complicates their estimation. The existence of various surface types and different exposures to solar radiation in a complex surface geometry can lead to significant variations in heat fluxes over short distances. This problem is well-known, but for practical purposes various simplifications that assume homogeneous properties at the surface like Monin–Obukhov Similarity Theory (MOST) are still widely used to estimate the sensible heat flux in meso-scale models, typically with the scalar roughness approach. Although MOST was originally derived for flat and homogeneous terrain, several studies have used it over heterogeneous terrain, including cities (Nadeau et al. 2009). In URBANFLUXES, the Aerodynamic Resistance Method (ARM) to estimate $Q_H$ uses the simple relation (e.g. Brutsaert, 1982):

$$Q_H = \frac{\rho c_p (T_s - T_a)}{r_a}, \tag{2}$$

where $\rho$ is the density of air, $c_p$ the specific heat of air at constant pressure, $T_s$ is surface temperature that can be calculated from the satellite thermal infrared observations, $T_a$ is the air temperature recorded by the meteorological stations, and $r_a$ is the aerodynamic resistance. Analogously to $Q_H$, $Q_E$ is expressed as:

$$Q_E = \frac{\rho c_p (e_s^* - e_a)}{\frac{r_a}{r_s} + \frac{1}{r_s}}, \tag{3}$$

where $e_s^*$ is the saturation water vapour pressure at the surface temperature, $e_a$ is the atmospheric water vapour pressure, $\gamma$ is the psychrometric constant and $r_s$ is the stomatal resistance. Stomatal resistance is calculated after Kato et al. (2008) using the simplified equation from Nishida et al. (2003):

$$\frac{1}{r_s} = \frac{f_1(T_a)f_2(PAR)}{r_{sMIN}} + \frac{1}{r_{cuticle}}, \tag{4}$$

where $PAR$ is the photosynthetic active radiation, $r_{sMIN}$ is the minimum stomatal resistance and $r_{cuticle}$ is the canopy resistance related to the diffusion through the cuticle layer of leaves. Functions $f_1$ and $f_2$ are calculated as per Nishida et al. (2003) and $r_{sMIN}$ can be determined for each vegetation type (Kato et al. 2008). $Q_E$ is calculated by land cover type and weighted by fraction of water, vegetation and pervious surfaces with the respective $r_{sMIN}$ in every pixel. The calculation of $r_s$ by eq. (4) is documented in detail in section 4.3.5.
The aerodynamic resistance $r_a$ for sensible heat in eq. (2) can then be written as (e.g. Voogt and Grimmond, 2000):

$$r_a = \frac{1}{u_*} \ln \left( \frac{z_{\text{ref}} - z_d}{z_{0m}} \right) - \psi_h \left( \frac{z_{\text{ref}} - z_d}{L} \right) + \ln \left( \frac{z_{0m}}{z_{0h}} \right)$$

and

$$u_* = U k \left[ \ln \left( \frac{z_{\text{ref}} - z_d}{z_{0m}} \right) - \psi_m \left( \frac{z_{\text{ref}} - z_d}{L} \right) - \psi_m \left( \frac{z_{0m}}{L} \right) \right]^{-1}$$

where $u_*$ is the friction velocity, $k$ is the von Karman constant (0.4), $z_{\text{ref}}$ refers to a reference height (usually the height of wind measurements), $z_d$ is the zero-plane displacement height, $L$ is the Monin-Obukhov length, $z_{0m}$ and $z_{0h}$ are the roughness lengths and $\psi_{m,h}$ are the stability functions for momentum and heat, respectively. Equation (6) can be used to estimate $u_*$ from wind velocity $U$, if no direct measurements of the friction velocity are available.

$$k\beta^{-1} = \ln \left( \frac{z_{0m}}{z_{0h}} \right)$$

In literature, reported values for $k\beta^{-1}$ show a large variability, even for similar types of surfaces. Lowest values of around 2 correspond to homogeneous vegetative surfaces (Brutsaert 1982), but also to flat semi-arid areas (Koshiek et al. 1993). Higher values are reported for heterogeneous surfaces and urban land use classes, e.g. with values around 20-27 for a light industrial site as reported by Voogt and Grimmond (2000). Kato and Yamaguchi (2007) list values for $k\beta^{-1}$ of 7 (industrial, urban, forest), 4.6 (grassland) and 3.9 (lawn, bare soil). Several studies used Eddy Covariance (EC) and/or scintillometry measurements to determine $k\beta^{-1}$ in the footprint of their measured fluxes. In URBANFLUXES this approach will be used later to evaluate results (D6.2). Here, we will use flux tower measurements as reference values for the magnitude of the fluxes of momentum and sensible and latent heat during the satellite overpass. $z_{0h}$ was calculated from the roughness Reynolds’ number (see section 4.3.5 and Equation (14)).

To determine the input parameters for $r_a$, the approach of Xu et al. (2008) is modified to the satellite data. Both, roughness length (for heat and momentum) and displacement height are needed in $r_a$ calculation. Input for the calculation of roughness parameters, i.e. the morphometry, is provided by [R2]. Roughness parameters are calculated using the real urban surfaces parameterization of Kanda et al. (2013) in section 4.3.4.

Consequently, the roughness length for $Q_H$ and $Q_E$, as well as the minimum stomatal resistance for latent heat flux need to be interpolated based on the urban morphology and the urban surface characteristics as they will be derived from EO. Standard meteorological observations and direct measurements from EC flux towers will be used to support the turbulent fluxes estimation from EO data. These observations are necessary to calibrate and
verify the satellite observations and include solar radiation, relative humidity, air pressure, air
temperature and wind speed measured at representative locations in case study areas.

3.2 Input data
Surface characteristics in the form of morphology and atmospheric conditions are essential in
the ARM-scheme. The following describes how to derive these parameters and the sources
which are used (Table 2). The goal of URBANFLUXES is to resolve the UEB components at a
resolution of 100 metre pixels (1 ha) across any urban area where the appropriate data are
available [R1].

Upscaling of the fluxes to the total area will be accomplished through the classification of
Local Climate Zones (LCZ) and/or other zoning techniques. See [R3] for further details.

Table 1. Data required for the estimation of sensible and latent heat flux by the ARM

<table>
<thead>
<tr>
<th>Needed for WP6 D6.1</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature ($T_s$)</td>
<td>EO</td>
</tr>
<tr>
<td>Atmospheric vapour pressure ($e_a$)</td>
<td>Sensor network</td>
</tr>
<tr>
<td>Air temperature ($T_a$)</td>
<td>Sensor network</td>
</tr>
<tr>
<td>- Saturation vapour pressure ($e_s$)</td>
<td>from $T_a$</td>
</tr>
<tr>
<td>Wind velocity, wind direction, friction velocity</td>
<td>Flux tower measurements</td>
</tr>
<tr>
<td>In-situ $Q_H$ and $Q_E$ for validation</td>
<td>Flux tower measurements</td>
</tr>
<tr>
<td>Roughness ($z_{mom}$, $z_{sh}$, $z_d$)</td>
<td>Morphometry, DSM &amp; DEM</td>
</tr>
<tr>
<td>Plan area index ($\lambda_p$)</td>
<td>Morphometry, DSM &amp; DEM</td>
</tr>
<tr>
<td>Frontal area index ($\lambda_f$)</td>
<td>Morphometry, DSM &amp; DEM</td>
</tr>
<tr>
<td>Mean, max and stdev of building height ($z_H$, $z_{Hmax}$, $z_{Hstd}$)</td>
<td>Morphometry, DSM &amp; DEM from morphometry, DSM &amp; DEM, flux towers, EO, LULC, literature values for comparison</td>
</tr>
<tr>
<td>Aerodynamic resistances ($r_a$, $r_s$)</td>
<td></td>
</tr>
</tbody>
</table>

4 CITY SCALE SENSIBLE AND LATENT HEAT FLUX: THE BASEL CASE STUDY

4.1 Datasets
The estimation of sensible and latent heat flux is tested for the Basel case study on 30 AUG
2015 1116 CET from a Landsat 8 scene. The scene was chosen because high heat fluxes are
expected. Results are presented for Basel test area with a 100 m grid to be compatible with
[R4]. Note that some input parameters are derived from higher resolution datasets in order
to profit from the higher accuracy.
4.2 Meteorological conditions, air temperature and humidity

The sensor network in Basel at the end of AUG 2015 (Table 3, Figure 2) was incomplete due to delivery problems and delays with permissions for the installation of stations. However, together with the permanent stations operated by UNIBAS and the service for air pollution (LHA), we have 13 locations with measurements of air temperature and humidity, including the two flux towers BKLI and BAES with other relevant variables (radiation, turbulent fluxes, friction velocity, etc.).

![Locations of Basel sensor network stations](image)

**Figure 1:** Locations of Basel sensor network stations. Refer to Tables 3 and 4 for more details and measurement values.

Meteorological conditions on 30 AUG 2015 1116 CET (Tables 3 and 4, Appendix) were very similar at the two flux towers (Table 4), except for latent heat flux, which is higher at BKLI due to larger vegetation fraction in the tower footprint. Flux footprints and source areas are subject to detailed investigation in D6.2 (Verification, uncertainty analysis and documentation of EO derived $Q_H$ and $Q_E$ fluxes). Measured air temperatures range from 29 to 32 °C, if the extreme value of 34 °C at LHA2 is not considered (Table 3). This station, operated by the air pollution service, is located in a sheltered, poorly ventilated location at street level and thus
not representative of a larger area. Therefore an air temperature of 29.5 °C at the reference height for the whole Basel test area is used initially in Equation (2) and to calculate \( e_s \) for Equation (3). Relative humidity ranges from 30 to 38 % at city stations, at the rural reference site BLER (grassland) a value of 56% is measured. Therefore values of 41 hPa for \( e_s \) and 14 hPa for \( e_a \), resulting in a vapour saturation deficit of 27 hPa, are used in Equation (3).

**Table 2.** Basel sensor network, data from stations shaded in grey were available on 30 AUG 2015. Grid coordinates are for UTM zone 31 N. Heights in metres are given both for above sea level (asl) and above ground level (agl), air temperature (\( T \)) and relative humidity (\( RH \)), where available.
Table 3. Meteorological conditions at flux towers on 30 AUG 2015 1116 CET.

<table>
<thead>
<tr>
<th>Variable (units)</th>
<th>BKLI</th>
<th>BAES</th>
<th>Range (all stations)</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation SW ↓↑ (W m⁻²)</td>
<td>761/87</td>
<td>770/83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation LW↓↑ (W m⁻²)</td>
<td>393/517</td>
<td>383/519</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net radiation (W m⁻²)</td>
<td>550</td>
<td>554</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensible heat flux (W m⁻²)</td>
<td>177</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat flux (W m⁻²)</td>
<td>91</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station pressure (hPa)</td>
<td>986</td>
<td>982</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friction velocity (m s⁻¹)</td>
<td>0.25</td>
<td>0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability index (z_H-z_d)/L</td>
<td>-2.2</td>
<td>-1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>1.8</td>
<td>1.6</td>
<td>0.5...1.7</td>
<td></td>
</tr>
<tr>
<td>Wind direction</td>
<td>NW</td>
<td>NNE</td>
<td>S,W,NW</td>
<td></td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>29.5</td>
<td>29.5</td>
<td>29...34</td>
<td>34 at LHA2</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>37</td>
<td>37</td>
<td>30...56</td>
<td>56 at BLER</td>
</tr>
</tbody>
</table>

4.3 Land Surface Temperature LST

Surface temperatures (Figure 3), derived from the Landsat 8 Thermal Infrared Sensor (TIRS) for 30th of August 2015 at 1116 CET, were resampled to the test area grid. This data is provided by deliverable D3.1 using the methods outlined therein [R2]. The highest LSTs (up to 43 °C) were observed in the most densely built-up areas, the industrial regions and at railway stations. Water bodies, i.e. the river Rhine, and forests show the lowest LSTs.

4.4 Morphometry and roughness parameters \( z_d \) and \( Z_{0m} \)

Morphometric parameters \( z_H, z_{H_{\text{max}}}, z_{H_{\text{std}}}, \lambda_0 \) and \( \lambda_f \) were derived from 1 m x 1 m digital surface model (DSM) for the Basel test area using UMEP (Urban Multi-scale Environmental Predictor, Lindberg et al. 2015). See [R2] and [R4] for further detailed information about derivation of morphometric parameters and UMEP. Roughness parameters \( z_d \) and \( Z_{0m} \) were then calculated according to Kanda et al. (2013), using the above morphometric values, a reference height of 4 m above the mean building height \( z_H \) and the modified Dyer (1974) stability functions from Högström (1988). The reference height of \( z_H + 4 \) m was chosen with the underlying assumption that this height must be somewhere close above mean roof level. Note that the following calculations are not very sensitive to this height within a range of a few meters.
Figure 2. Surface temperatures derived from Landsat 8 scene 30 AUG 2015 1116 CET, resolution 100 m x 100 m (resampled from original 90 m resolution), stations with meteorological measurements (green dots), and inactive stations (black) at time of satellite overpass. Grids coordinates are for UTM zone 31 N.

The Kanda et al. (2013) modification to Macdonald (1998) is used with the real urban surfaces parameters. This uses mean building height $z_H$, its maximum $z_{Hmax}$, its standard deviation $z_{Hstd}$, plan area index $\lambda_p$ and frontal area index $\lambda_F$. For the zero-plane displacement height $z_d$ (Kanda et al. 2013):

$$\frac{z_d}{z_{Hmax}} = c_0X^2 + (a_0\lambda_p^0 - c_0)X$$  \hspace{1cm} (8)
with \[ X = \frac{x_{Hstd} + x_H}{z_{Hmax}}, \quad 0 \leq X \leq 1.0 \] (9)

where \( a_0, b_0, \) and \( c_0 \) are the regressed constant parameters, i.e., \( 1.29, 0.36, \) and \( -0.17, \) respectively; and for the roughness length for momentum \( z_{0m} \):

\[
\frac{z_{0m}}{z_{0(mac)}} = b_1 Y^2 + c_1 Y + a_1
\] (10)

where \[ Y = \frac{\lambda_p z_{Hstd}}{z_H}, \quad Y \leq 0 \] (11)

with the regression constants \( a_1 = 0.71, b_1 = 20.21 \) and \( c_1 = -0.77, \) and \( z_{0(mac)} \) from the Macdonald (1998) equations:

\[
\frac{d}{z_H} = 1 + A^{-\lambda_p} (\lambda_p - 1)
\] (12)

\[
\frac{z_{0(mac)}}{z_H} = \left(1 - \frac{d}{z_H}\right) \exp \left[-\left\{0.5\beta \frac{c_{lb}}{k^2} \left(1 - \frac{d}{z_H}\right) \lambda_f\right\}^{0.5}\right]
\] (13)

where \( A \) and \( \beta \) are parameters with values of 4.43 and 1.0, respectively, \( c_{lb} = 1.2 \) is the drag coefficient of an obstacle and \( k \) the von Karman constant (0.4).

The calculated \( z_d \) and \( z_{0m} \) (Equation 8 and 13) are shown in Figures 4 and 5.
Figure 3. Zero-plane displacement height $z_d$ as calculated by Equation (8).
4.5 Aerodynamic resistances

Aerodynamic resistance for heat $r_{oh}$ was calculated according to Equation (5) using the Brutsaert (1982) equation for the excess resistance $z_{0h}$ when using radiometric temperatures. Here we apply the value of the coefficient $\alpha$ adapted to urban surfaces by Kanda et al. (2007) and Kanda and Moriizumi (2009):

$$z_{0h} = z_{0m}[7.4 \exp(-\alpha Re_0^{0.25})]$$

(14)
where $\alpha = 1.29$ and $Re^* = \frac{z_0 u^*}{\nu}$ is the roughness Reynolds number with a kinematic molecular viscosity $\nu$ of $1.461 \times 10^{-5}$ ms$^{-1}$. This $z_0$ value is used in Equation (7) for the calculation of aerodynamic resistance $r_{ah}$. Values for $r_{ah}$ are shown in Figure 6.

**Figure 5.** Aerodynamic resistance $r_{ah}$ at the time of the overflight at reference height $z_H + 4$ m

Stomatal resistance $r_s$ for vegetated surfaces is calculated by Equation (4) using the values for $r_{sMIN}$ in Table 5. $PAR$ was taken as $f\cdot SW\downarrow$, the incoming shortwave radiation. For $f$ we used $2.05$ $\mu$mol m$^{-2}$ s$^{-1}$ as proposed by Nishida et al. (2007). The following relations apply for $f_1(T_a)$ and $f_2(PAR)$ in Equation (4):
\[ f_1(T_a) = \left( \frac{T_a - T_n}{T_o - T_n} \right) \left( \frac{T_x - T_a}{T_x - T_o} \right) \frac{(T_x - T_o)/(T_o - T_n)} \]

where \( T_a \) is air temperature, \( T_n \) is the minimum (2.7 °C), \( T_o \) the optimal (31.1 °C) and \( T_x \) (45.3 °C) the maximum temperature for stomatal activity, respectively. \( f_2(PAR) \) is calculated as \( f_2(PAR) = (PAR)/(PAR+A) \), with \( A = 152 \ \mu\text{mol m}^{-2} \ \text{s}^{-1} \) as the parameter for photon absorption efficiency at low light intensity. This set of parameters is considered as representative for all biomes (Nishida et al. 2003) for the time being, but may be adapted to city specific conditions in further calculations of \( r_s \).

### 4.6 Land cover fractions

To estimate \( Q_E \) fractions of transpiring surfaces are needed. In order to have the most precise information, multi-temporal pan-sharpened (Gram-Schmidt, 15 m pixels size) Landsat 8 scenes (YYYY-DOY: 2013-156, 2014-159, 2014-198, 2015-162, 2015-185, 2015-217, 2015-242) were used with the Maximum Likelihood Classifier. The modal value of the seven scenes was computed for every pixel containing a non-vegetation class. Thereafter, the “true” value of one pixel is taken to be with the highest mode class in this pixel. Vegetation classes are date specific. See Laben and Brower (2000) for a complete overview of the pan-sharpening method.

Land use classes were assigned based on a priori understanding of the city structure. “Dense Urban” covers the Basel old town with midrise buildings with low sky view factors and vegetation fractions. “Urban” areas have typical housing (3-6 stories) of the city with midrise buildings, medium size streets (15-25 m width) with larger sky view factors and with vegetation in the backyard of the buildings. The “Suburban” class includes individual low-rise buildings surrounded by small private gardens with smaller building fractions compared to “Urban”. “Urban Rural” contains all types of urban gardening or graveyards. The two industrial classes are “Industrial 1” with large roads, rails and concrete squares (Roads/Rails/Concrete) and “Industrial 2” with large midrise to high-rise buildings, bright roofs and high imperviousness. The agricultural classes differ in the kind of cultivation. Wheat and other cereals that appear bright in an RGB image (Agriculture Yellow) were distinguished from corn, grass or other rather greenish plants (Agriculture Green). Vineyard/Shrub is concentrated on some hillside parts with large vineyards, but also widely scattered. The Forest/Plantation class contains all mid-rise or high-rise trees, therefore besides the large forests also some orchards. The water class is dominated by the river.
Figure 6. Land Use/ Land Cover (LULC) for 30 AUG 2015 (see text for methods and descriptions)
Table 4. Minimum stomatal resistance $r_{sMIN}$ (adapted from Kato and Yamaguchi, 2007) and calculated stomatal resistance $r_s$ for transpiring LULC classes from Equation (7)

<table>
<thead>
<tr>
<th>LULC</th>
<th>$r_{sMIN}$ (s m$^{-1}$)</th>
<th>$r_s$ (s m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture yellow</td>
<td>500</td>
<td>551</td>
</tr>
<tr>
<td>Agriculture green</td>
<td>90</td>
<td>99</td>
</tr>
<tr>
<td>Shrubs/vineyard</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Forest/Plantation</td>
<td>60</td>
<td>66</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 7. Dimensionless parameter $k \theta^{-1}$ as calculated from Equation (7) for time of the overpass.

4.7 Sensible heat flux $Q_H$ on a pixel base

Figure 9 shows the estimated sensible heat flux $Q_H$ for the LANDSAT scene from 30 AUG 2015 1116 CET. The spatial pattern is dominated by the fractions of transpiring and impervious surfaces in a 100 m x 100 m pixel. The highest sensible heat fluxes are found in the most densely built-up regions with high surface temperatures and missing vegetation. Industrial areas particularly show high fluxes up to 300 W m$^{-2}$ and more.
Figure 8. Sensible heat flux $Q_H$ in W m$^{-2}$ on 30 AUG 2015 at 1116 CET covering the central parts of Basel, Switzerland. White pixels have no roughness data available.

4.8 Latent heat flux $Q_E$ on a pixel base

Figure 10 shows the estimated latent heat flux $Q_E$ for the LANDSAT scene from 30 AUG 2015 1116 CET. The spatial pattern is dominated by the fractions of transpiring surfaces in a 100 m x 100 m pixel. Highest evapotranspiration rates are found over forests and parks with a
considerable amount of trees. The Rhine River additionally shows increased evaporation compared to the densely built-up and impervious areas.

Figure 9. Latent heat flux $Q_e$ in W m$^{-2}$ on 30 AUG 2015 at 1116 CET covering the central parts of Basel, Switzerland. White pixels have no roughness data available.
5 CONCLUDING REMARKS AND FUTURE ACTIVITIES

The first estimates of spatially derived fluxes of sensible and latent heat show reasonable magnitudes and patterns. They compare well to eddy covariance (EC) measurements in the EC source area. A complete verification and uncertainty analysis is the subject of Deliverable D6.2 and therefore out of the scope of this document. During the next months, data from the other case study cities (London and Heraklion) will be processed. The area in Basel will be extended as the needed base data (e.g. urban morphology) and measurements from the sensor networks become available. Future work includes a number of different activities related to the calculation of aerodynamic resistances including vegetation fractions from unmixing of Sentinel-2 data. Sensitivity studies of the applied algorithms will improve the accuracy of flux estimates. Additionally, the seasonal variation of stomatal resistances and the diurnal variation of $k\beta^{-1}$ will be investigated.

The next milestone for WP6 is the main product of WP6 which will be delivered to WP7 for further processing: the Deliverable 6.2 “Report on cross-checking $Q_H$ and $Q_E$ fluxes with independent methods and measurements and the documentation of the database of the final $Q_H$ and $Q_E$ products” to be submitted on M18. Finally, by the end of the project (M36) the Deliverable D6.3 “Case studies measurements” will be submitted. It will be a database containing all in-situ measurements performed at all case study areas during the project’s lifecycle.

6 REFERENCES


7 APPENDIX

7.1.1 Diurnal courses of meteorological variables on 30 AUG 2015

Figure A1: Flux towers BKLI (solid) and BAES (dotted)
**Figure A2:** BKLB (black), BKLS (black dotted), BLEO (red), BLER (green), BBIN (blue)
Figure A3: UFB2 (red), UFB3 (green), UFB4 (green dotted), UFB5 (blue), LHA1 (black), LHA2 (black dotted).