6 Cooling by vegetation and water in urban areas

6.1 Overview

Urban areas heat up more than the surrounding rural areas due to the Urban Heat Island (UHI) effect. This additional heating occurs due to the higher absorption of sunlight by darker materials such as asphalt and concrete, and a slower release of this heat by these materials, a reduced wind speeds between buildings and less natural evaporation because of soil sealing. The additional heat can cause health problems during warm periods, especially for the elderly and young infants (e.g. Kovats & Hajat, 2008).
The availability of vegetation and water can have a positive effect on the cooling capacity of urban areas, as they increase the evaporation capacity of an area, can provide shade and release heat quicker than sealed areas. In this model, the cooling effect of vegetation and water on the UHI are calculated.
Five output maps have been developed for the Atlas of Natural Capital for the ecosystem service 'cooling in urban areas' (see Table 6.1). The output map has been produced by combining existing spatial data for the Netherlands with maps developed by RIVM for the Natural Capital Model. Tables 6.1 and 6.2 provide an overview of the input and output maps in order to model the ecosystem service 'cooling in urban areas'.
The five output maps show what the maximum UHI effect in an area would be based on population density and average wind speed, and how vegetation, water and soil sealing affect the UHI at different scales (1 km, 30 m, single cell), as well as the overall cooling effect of urban green and water.

Table 6.1. Output maps generated for the ecosystem service 'cooling in urban areas'.

Output map	Unit	Short description
Maximum UHI effect	°C/cell	Maximum average annual urban heat island effect that could occur, given population density and average wind speeds.
Potential UHI effect	°C/cell	The UHI effect that can be expected based on the amount of soil sealing in a 1 km radius.
In situ cooling effect of urban green and water	°C/cell	The cooling effect of land cover in a given cell, without taking into account its surroundings.
Actual local UHI effect	°C/cell	The cooling effect of vegetation and water in the direct surroundings of a location (30 metres).
Cooling effect of urban green and water	°C/cell	The cumulative cooling effect of vegetation and water in urban areas.

Table 6.2. Input maps applied to estimate the ecosystem service 'cooling in urban areas'.

Input	Unit	Short description	Source
Wind speed	m s-1	Average wind speed at 100 m height in the period 2004-2013.	KNMI (Geertsema & van den Brink 2014)
Inhabitants	# inhabitants per cell	Shows the number of inhabitants per cell	RIVM (Appendix II)
Ecosystem unit map	Ecosystem unit classes	Ecosystem unit classes map for the Netherlands in 2013	CBS 2017
Trees	% cover per cell	Shows the percentage of a cell that is covered by trees taller than 2.5 metres.	RIVM (see Appendix I)
Bushes and shrubs	% cover per cell	Shows the percentage of a cell that is covered by bushes and shrubs between 1 and 2.5 metres tall.	RIVM (see Appendix I)
Low vegetation	% cover per cell	Shows the percentage of a cell that is covered by vegetation that is lower than 1 metre.	RIVM (see Appendix I)
Vegetation cover	% cover per cell	Shows the percentage of a cell that is covered by vegetation (low vegetation, bushes and shrubs and trees combined).	RIVM (see Appendix I)
Percentage non-green area	% cover per cell	Shows the percentage of a cell that is not covered by vegetation (the inverse of the map 'Vegetation cover').	VITO

6.2 Modelling the ecosystem service

The service 'cooling by vegetation and water in urban areas' results in five output maps. The modelling of these five maps is described in the following sections. The model assesses the effects of paved surfaces, vegetation and water at three levels: local (within 30m, Sections 6.2.2 and 6.2.3), neighbourhood (within 1 km, Section 6.2.4) and city (within 10km, Section 6.2.5). The method presented in Section 6.2.1 show the cumulative result of these three levels. Figure 6.2 provides a schematic overview of the way input data has been modelled in order to produce the output maps for the ecosystem service 'cooling in urban areas'.

6.2.1 Cooling effect of urban green and water

The cooling effect of urban green and water can be calculated as the difference between the maximum Urban Heat Island (UHI) effect in an urban area and the actual local UHI effect:

$$\textit{Cooling effect urban green and water} = \textit{Maximum UHI effect} - \textit{Actual local UHI effect}$$

As the cooling effect of green and water is modelled for urban areas, in the output map only areas with at least 20% sealed areas in a one km radius around a cell have been included, using the intermediate map for *%soil sealing1km* variable that is described in Section 6.2.4 and imposing a minimum threshold of 20%. This threshold was chosen to include all urban areas and some of the direct surroundings, but to exclude predominantly rural areas for which the UHI effect is not relevant. The threshold was applied predominantly for visual purposes and does not affect the values in cells that have a higher soil sealing percentage than 20%. The calculation results in the map 'Cooling effect of urban green and water'.

6.2.2 *Actual local UHI effect*

Vegetation and water have a cooling effect on their direct surroundings (e.g. by providing shade and circulating moisture). As the distance at which the effect can be felt is still under discussion in scientific literature, a conservative estimate of 30 m has been applied for this model. To calculate the local cooling effect of vegetation and water, the percentages of all land uses in a 30 m radius around a pixel was calculated and the respective reductions from Tables 6.3 and 6.4 were applied. The local UHI was calculated as follows (Function 3, Figure 6.2):

$$\textit{Actual Local UHI}_i = \textit{Potential UHI}_i * \left(1 - \sum fr\,Reduction_{type30m}\right)$$

Where *Actual Local* UHI_i is the local UHI effect of cell *i*, taking into account the cooling effect of local vegetation and water in a 30m radius, *Potential* UHI_i is the potential UHI effect of cell *i* as calculated in Section 1.2.4, and $frReduction_{type30m}$ is the percentage reduction of the UHI effect of the land cover types in a 30m radius around cell *i*, following Tables 6.3 and 6.4. For example, in a cell with a potential UHI of 3°C that has 20% trees, 20% grass, 10% water and 50% built-up area within a 30m radius, the local UHI is obtained as follows:

3 * (1 – (0.2*0.5 + 0.2*0.2 + 0.1*0.3 + 0.5*0) = 2.49°C.

UHI reduction rates of land cover types

Based on expert judgement, the vegetation from the vegetation cover maps (trees, bushes and low vegetation cover maps (Appendix I)) were assigned maximum UHI effect reduction rates in percentages (Table 6.3) and the land cover types in the LCEU map were assigned reduction rates (Table 6.4).

Table 6.3. Applied reduction of UHI effect by vegetation types from vegetation cover maps based on expert judgement. These percentages were used as input for the model.

Vegetation maps	Reduction UHI effect (%)
Trees	50
Shrubs and bushes	30
Low vegetation	20

Table 6.4. Applied reduction of UHI effect by LCEU land cover classes based on expert judgement. These percentages were used as input for the model.

Land cover type LCEU map	Reduction UHI effect (%)
Built-up area	0
(Semi)natural vegetation	20
Inland water	30
Sea	100
Agricultural land	15-30
Bare soil	0

6.2.3 *In situ cooling effect of vegetation and water*

To calculate the cooling effect of a cell on its surroundings, the in situ cooling effect needs to be calculated. The vegetation types and water have a different impact on cooling and most types cannot completely compensate for the UHI effect (Tables 6.3 and 6.4). To determine the UHI reduction per cell, four input maps were used: the tree cover map, the bushes and shrubs cover map, the low vegetation cover map and the map with the percentage of non-green area. The map showing the percentage of non-vegetated areas was generated as the inverse of the summed-up vegetation cover map. To calculate the UHI reduction of from the non-green area map, the LCEU land cover types are used. The in situ cooling effect of vegetation and water is calculated as follows (Function 2, Figure 6.2):

$$\boldsymbol{In\ situ\ cooling\ effect\ vegetation\ and\ water_i} \\ = \boldsymbol{Potential\ UHI_i \times fr\ Reduction_{type\ i}}$$

Where the *In situ cooling effect of vegetation and water*$_i$ is the cooling effect of vegetation and water for cell *i* in °C, *Potential UHI*$_{i,}$ is the potential UHI effect of cell *i, frReduction*$_{type\ i}$ is the reduction fraction of the UHI effect of the land cover type in cell *i,* following Tables 6.3 and 6.4. The result of this calculation is the map 'In situ cooling effect of urban green and water'.

6.2.4 *Potential UHI effect*

The potential UHI effect is determined by refining the city level analysis (Section 6.2.5), by analysing the effects of paved and unpaved surfaces within a one km radius of a certain location. To determine whether the

maximum UHI effect was reached in a given cell, the percentage of soil sealing was determined for the surrounding one km. The UHI effect only exists in built-up areas, so a certain degree of soil sealing must be present in the surroundings. The percentage of soil sealing is used to determine the potential UHI effect that can occur in a given area, based on a linear relation between the maximum UHI and zero. The radius of one km was based on expert judgement.
The percentage of soil sealing is determined on the basis of the LCEU land cover map (for built-up areas and water) and the vegetation cover map. The LCEU map is reclassified on a binary soil sealing map based on whether a land cover type is built-up or not (look-up table for 'soil sealing'). Built-up areas in the LCEU map were considered to have 100% soil sealing. The vegetation cover map was used to correct for the percentage of soil sealing in built-up areas based on the inverse of the percentage of coverage by vegetation of a pixel. For example, a road side with 30% vegetation was given a soil sealing value of 0.7 (1 – 0.3).
The potential UHI for a given location was calculated as follows:

$$\boldsymbol{Potential\ UHI_{i,j} = Maximum\ UHI_{i,j} \times frSoil\_sealing_{1km}}$$

Where *Potential UHI*$_i$ is the potential UHI effect of cell *i, Maximum UHI*$_i$ is the maximum UHI effect in cell *i* (based on the Maximum UHI effect map), and *frSoil_sealing*$_{1km}$ is the percentage of soil sealing in a one km radius around cell *i.* The result of this calculation is the 'Potential UHI effect' map.

6.2.5 *Maximum UHI effect*

The UHI effect is limited to a certain maximum on an annual average basis, given several constraints. To determine the maximum UHI effect that can occur in an area, an equation based on the relationship between the UHI effect, on the one hand, and the combination of wind speed and population density, on the other, was used. The equation resulted from the UrbClim model that was validated and used during the EU FP7 project RAMSES for 100 European cities (De Ridder et al., 2015; Lauwaet et al., 2015; Lauwaet et al., 2016). Results from the RAMSES project show that the maximum UHI effect can be estimated accurately based on two variables: (1) annual average wind speed at 10m above ground and (2) population size within a 10 km radius (Figure 6.1). Therefore, these variables have been adopted in this model. The equation used to model the maximum UHI is (Function 1, Figure 6.2):

$$\boldsymbol{Maximum\ UHI = -1.605 + 1.062 \times \log(population_{10km}) - 0.356 \times wind\ speed_{10m}}$$

Where *population*$_{10km}$ is the total population that lives within a 10 km radius around a given cell and *wind speed*$_{10m}$ is the average wind speed at 10m above ground. The low asymptote has been set at 0.
The average wind speed map at 100 metres above ground for the Netherlands, developed by KNMI, has been downscaled to a wind speed map for 10m above ground with a 10m spatial resolution. To downscale the wind speed at 100m above ground to wind speed at 10m above ground, the LCEU land cover map and the corresponding land cover types were used. Each land cover type has a corresponding 'roughness length for momentum' (z0m), which is equivalent to the height at which

the wind speed theoretically becomes zero for the given land cover type. The z0m for the LCEU land cover types were determined based on De Ridder & Schayes (1997) and are found in the look-up table 'Roughness length for momentum'. The wind speed at 10m above ground was determined, based on the following equation (Wieringa, 1986):

$$\boldsymbol{wind\ speed_{10m}} = \boldsymbol{wind\ speed_{100m}} \times \ln(10/z0m_{lc}) \,/\, \ln(100/z0m_{lc})$$

Where *wind speed*$_{10m}$ is the average wind speed at 10m above ground, *wind speed*$_{100m}$ is the average wind speed at 100m above ground and $z0m_{lc}$ is the roughness length for momentum of a given land cover type. The wind speed map was smoothed by calculating the value of the average wind speed in a 50m radius around a given cell and applying this value to the cell. This map was used for the variable *wind speed*$_{10m}$. Note: this step is not shown in the schematic diagram (Figure 6.2). The population in a 10km radius was calculated by summing the inhabitants in a 10km radius around a given cell on the inhabitants map developed by RIVM (Appendix II). This map was used for the variable *population*$_{10km}$.

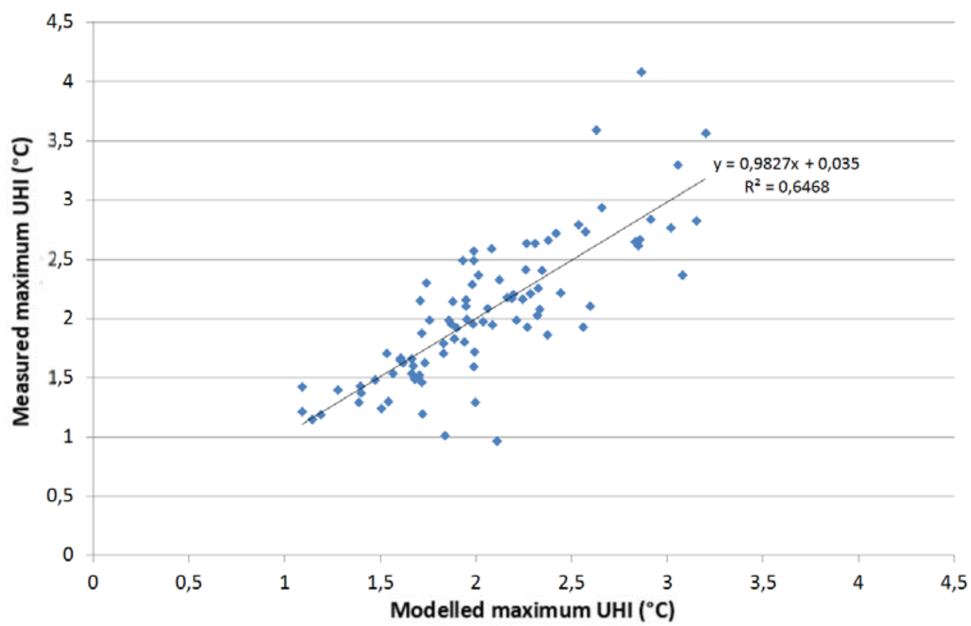

Figure 6.1. Relationship between the maximum UHI effect of a city and the variables 'wind speed' and 'population'. The blue dots indicate separate cities from the RAMSES project.

6.3 Remarks and points for improvement

- An important note for this model is that it shows the annual average UHI effect and takes into account both day and night temperatures. Temperature differences for a single period (e.g. a hot summer night) between an urban area and its surroundings could be much greater.
- The exact cooling effects of different types of vegetation have now been estimated based on expert knowledge, but not on empirical data. When such data becomes available for specific

vegetation and land cover types, the cooling effects in the model can be updated.
- The radius of local effects of vegetation and water has been conservatively estimated to be 30m. Some studies have estimated the effect could potentially have a cooling effect up to 250m distance, although current evidence is inconclusive. The distance effects in the model can be updated if new knowledge becomes available.

6.4 References

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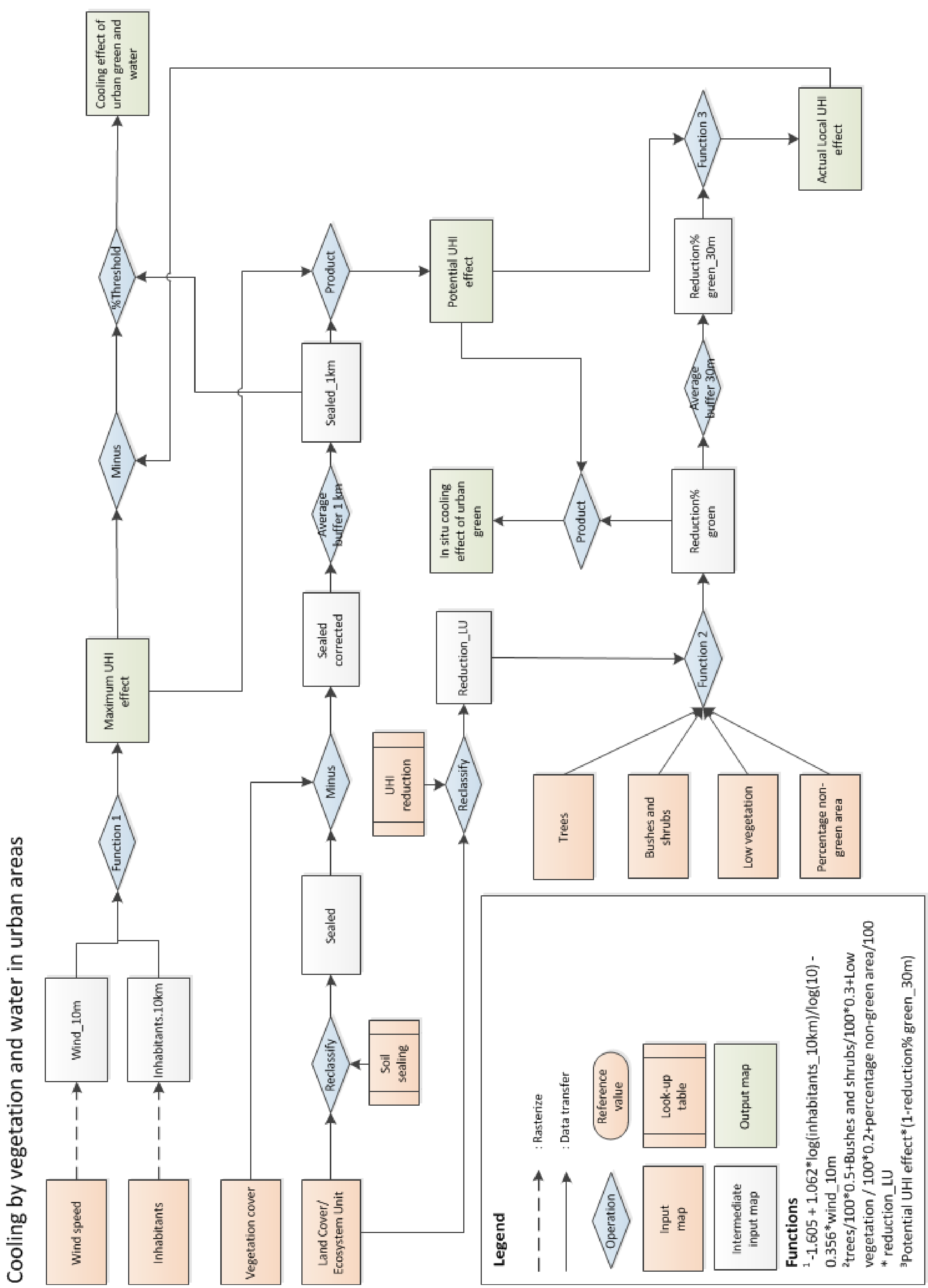

Figure 6.2. Schematic overview of 'Cooling in urban areas' model