Netherlands Natural Capital Model - Technical Documentation

Developed for the Atlas of Natural Capital (www.atlasnatuurlijkkapitaal.nl)

Cooling by vegetation and water in urban areas

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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 higher absorption of sunlight by darker materials such as asphalt and concrete, and a slower release of this heat by these materials, 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.

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 mapped.

Four output maps have been modelled for the Atlas of Natural Capital for the ecosystem service 'cooling in urban areas' (see Table 2.1). The output maps have been produced by combining existing and newly developed methodologies to model the input maps presented in Section 2. All models were developed by the Flemish Institute for Technological Research (VITO) and the National Institute for Public Health and the Environment of the Netherlands (RIVM) and will be explained in de next sections.

2. Methodology

Output maps have been produced by making use of functions and look-up tables to model data from input maps and reference values. In general three types of input data were used to model each output map:

1. **Input maps:** Spatial datasets with environmental, socio-economic and geographical information.
2. **Look-up tables:** Literature- and expert-based tables to reassign and reclassify units between maps.
3. **Reference values:** Values from scientific literature that are used in calculations in the model. *Note: for the 'Cooling in urban areas' model no reference values have been used.*

2.1 Input and output files

Table 2.1 provides an overview of the five output maps produced for the service ‘cooling in urban areas’. Information on the input sources (i.e. input maps and look-up tables) adopted for producing output maps is presented in Table 2.2.

Table 2.1 Ecosystem service output maps available for ecosystem service ‘cooling urban area’

CICES category	Ecosystem service	Output map	Unit
REGULATION Maintenance of physical, chemical, biological conditions	Cooling urban areas	Maximum UHI effect*	°C
		Potential UHI effect*	°C
		In situ cooling effect of urban green and water*	°C
		Actual UHI effect	°C
		Cooling effect of urban green and water	°C

* Output maps not published on the Atlas of Natural Capital website.

Table 2.2 Input and output maps for the ‘cooling urban area’ ecosystem service. The names of the input-map data files can be found in Appendix

Input	Unit	Short description	Source
INPUT MAP			
Wind speed	$m\ s^{-1}$	Average wind speed at 100 m height in the period 2004-2013.	Royal Netherlands Meteorological Institute (KNMI)
Inhabitants	# inhabitants per cell	Shows the number of inhabitants per cell	RIVM
Land cover/ecosystem unit map 2013	[-] Categories for land cover and ecosystem type	Land cover and ecosystem units map, depicting land cover/ecosystem classes for the Netherlands in 2013.	Statistics Netherlands (CBS)
Trees	% cover per cell	Shows the percentage of a cell that is covered by trees higher than 2,5 meters.	RIVM
Bushes and shrubs	% cover per cell	Shows the percentage of a cell that is covered by bushes and shrubs between 1 and 2,5 meters high.	RIVM
Low vegetation	% cover per cell	Shows the percentage of a cell that is covered by vegetation that is lower than 1 meter.	RIVM
Vegetation cover	% cover per cell	Shows the percentage of a cell that is covered by vegetation (low vegetation, bushes and shrubs and trees combined).	VITO
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
LOOK-UP TABLE			
Roughness length for momentum	[-]	Roughness length for momentum is equivalent to the height at which the wind speed theoretically becomes zero for different land cover types.	De Ridder, K., and G. Schayes (1997).
UHI reduction	Percentage	The cooling effect of land cover and vegetation on the maximum UHI.	VITO
Soil sealing	Binary	Determines which land cover types cause soil sealing (1) and which do not (0).	VITO

2.2 Modelling ecosystem service maps

Figure 2-1 provides a schematic overview of the way input data has been modelled in order to produce the output maps for the ecosystem service ‘cooling urban area.’ The individual steps that are taken in the model are explained below Figure 2-1. Five maps are generated from the model. The map ‘maximum UHI effect’ shows the maximum annual average temperature increase that can occur due to the UHI effect in a given location, based on average annual wind speed and population density of the surrounding area. The map ‘potential UHI effect’ shows the UHI effect that can be reached if soil sealing of the surrounding area (1km radius) is taken into account in addition to the maximum UHI. The degree of soil sealing of the surroundings indicates the amount of built-up area, which captures and holds more heat than vegetation, water and unsealed areas. The map ‘in situ cooling effect of urban green and water’ shows how much cooling green and water provide within a given grid cell, based on type and coverage. The map ‘actual local UHI effect’ applies further detail to the ‘potential UHI effect’ map by taking into account local vegetation (within a 30m radius) around a given area, and the additional cooling effect this vegetation has on its direct surroundings. The map ‘cooling effect of urban green’ shows how much green areas and water contribute to cooling urban areas (in °C).

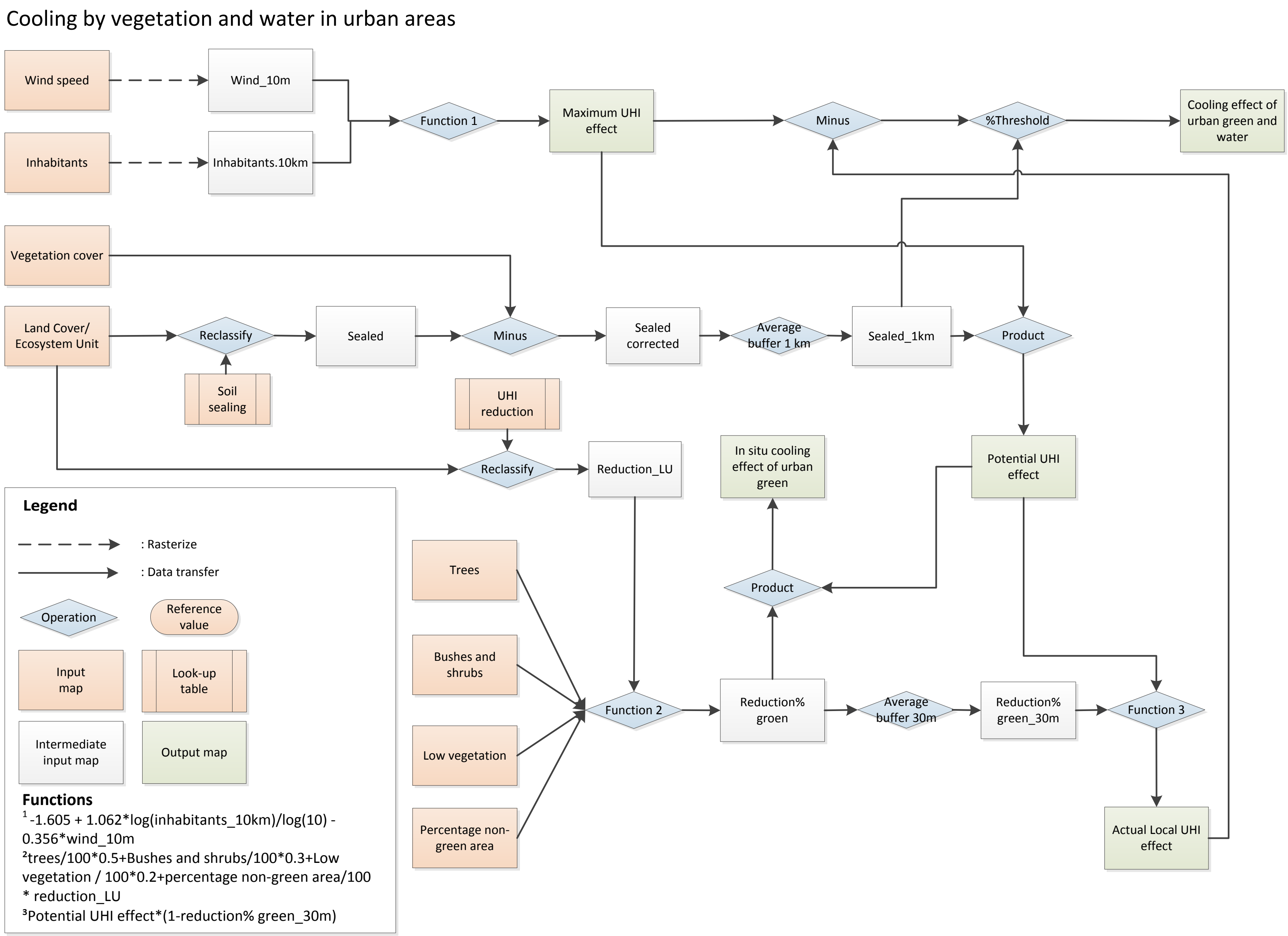

Figure 2-1 Schematic overview of 'cooling urban area' model

Step 1: Determining the maximum UHI effect

1.1 To determine the maximum UHI effect an equation based on the relation between the UHI effect on one hand and the combination of wind speed and population density on the other hand 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 average daily UHI effect can be estimated accurately based on two variables: (1) annual average wind speed at 10m height and (2) population size within a 10 km radius (Figure 2-2). Therefore, these variables have been adopted in this model. The equation used to model the maximum UHI is:

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

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 height. The low asymptote has been set at 0.

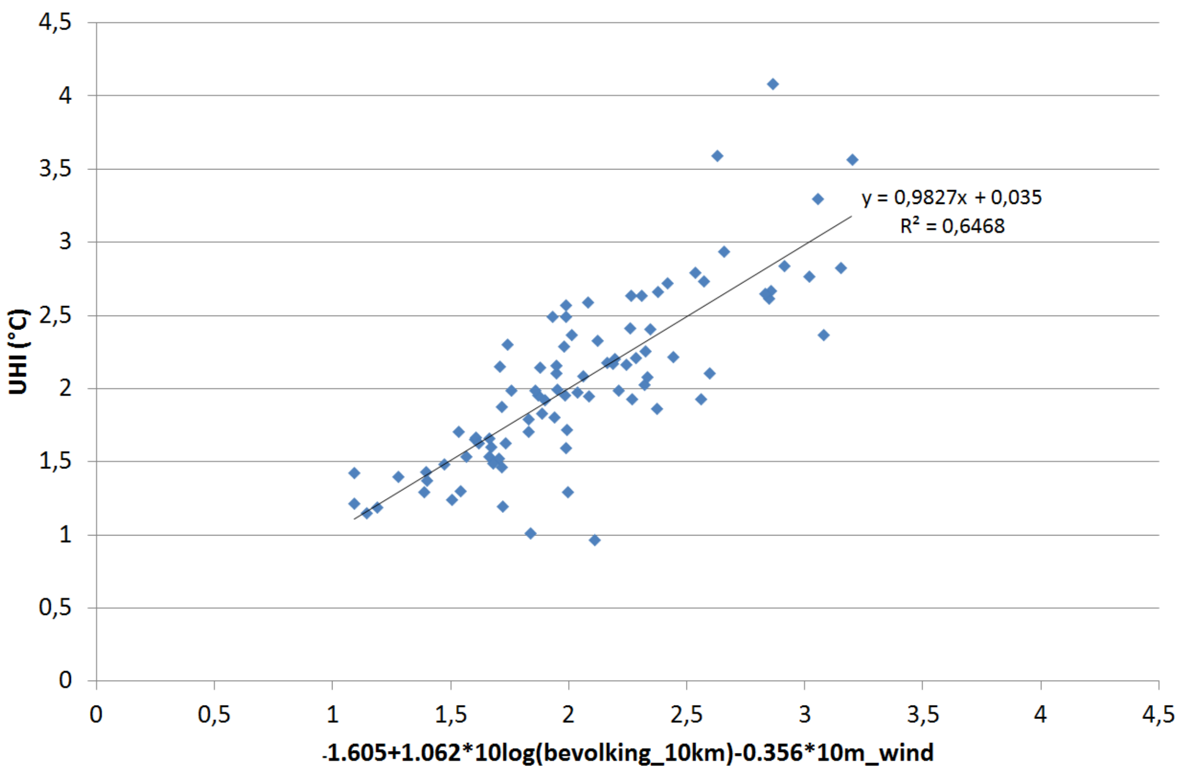

Figure 2-2 Relation between the maximum UHI effect of a city and the variables 'wind speed' and 'population'.

1.2 The average wind speed map at 100 meters height for the Netherlands, developed by KNMI, has been downscaled to a wind speed map for 10m height with a 10m spatial resolution. To downscale the wind speed at 100m height to wind speed at 10m height 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 height 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 height, *wind speed*$_{100m}$ is the average wind speed at 100m height 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.

1.3 The population in a 10km radius was calculated by summing the inhabitants in a 10km radius around a given cell of the inhabitants map developed by RIVM. This map was used for the variable *population*$_{10km}$.

1.4 The map 'Maximum UHI' effect was calculated using the maps for *wind speed*$_{10m}$ and *population*$_{10km}$ and the equation introduced in step 1.1.

Step 2: Determining the potential UHI effect

2.1 To determine whether the maximum UHI effect was reached in a given cell, the percentage of soil sealing was determined for the surrounding 1km. The UHI effect only exists in built-up areas, so a certain degree of soil sealing must be available 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 1km was based on expert judgement.

2.2 The percentage of soil sealing is determined based on the LCEU land cover map and the vegetation cover map. The LCEU map is reclassified to a binary soil sealing map based on whether a land cover type is built-up or not (look-up table '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 of built-up areas, based on the inverse of the percentage coverage by vegetation of a pixel. For example, a road side with 30% vegetation got a soil sealing value of 0.7 (1 – 0.3).

2.3 The potential UHI for a given location was calculated as follows:

$$\boldsymbol{Potential\ UHI_{i,j}} = \boldsymbol{Maximum\ UHI_{i,j}} \times \%\boldsymbol{soil\ sealing_{1km}}$$

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 *%soil sealing*$_{1km}$ is the percentage soil sealing in a 1 km radius around cell *i.*

2.4 The result of this calculation is the map 'Potential UHI effect'.

Step 3: Determining the in situ cooling effect of vegetation and water

3.1 Vegetation and water affect cooling of urban areas at a local scale, although they cannot completely compensate the UHI effect in cities. Different types of vegetation and water have different impact on cooling. 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 percentage non-green area. The percentage of non-vegetated areas map was generated as the inverse of the summed vegetation cover map. To calculate the UHI reduction of the percentage non-green area map, the LCEU land cover types are used.

3.2 Based on expert judgement the vegetation from the vegetation cover maps (trees, bushes and grass cover maps) were assigned maximum UHI effect reduction rates in percentages (Table 2.3) and the land cover types in the LCEU map have been assigned reduction rates (Table 2.4)). For reduction rates per LCEU class see look-up table 'UHI reduction'.

Table 2.3. Reduction of UHI effect by vegetation types from vegetation cover maps.

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

Table 2.4. Reduction of UHI effect by LCEU land cover classes.

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

3.3 The cooling effect of vegetation and water is calculated as follows:

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

Where *In situ cooling effect vegetation and water*$_i$ is the cooling effect of vegetation in water for cell *i* in °C, *Potential UHI*$_{i,}$ is the potential UHI effect of cell *i, %Reduction*$_{type\ i}$ is the percentage reduction of the UHI effect of the land cover type in cell *i,* following Table 2.3 and Table 2.4.

3.4 The result of this calculation is the map 'In situ cooling effect of urban green and water'.

Step 4: Calculation of actual local UHI effect

4.1 Vegetation and water have a cooling effect on their direct surroundings (e.g. by providing shade, and pumping around 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.

4.2 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 Table 2.3 and 2.4 were applied. The local UHI was calculated as follows:

$$\boldsymbol{Local\ UHI_i = Potential\ UHI_i * \left(1 - \sum \%\, Reduction_{type30m}\right)}$$

Where *Local* $UHI_{i,}$ is the local UHI effect of cell *i*, taking into account the cooling effect of local vegetation and water, *Potential* $UHI_{i,}$ is the potential UHI effect of cell *i* as calculated in step 3, $\%Reduction_{type30m}$ is the percentage reduction of the UHI effect of the land cover types in a 30m radius around cell *i,* following Table 2.3 and Table 2.4. 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.

4.3 The result of this calculation is the map 'Actual UHI effect'.

Step 5: Calculation of the cooling effect of urban green and water

5.1 The cooling effect of urban green and water can be calculated as the difference between the maximum UHI effect and the actual UHI effect:

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

5.2 As the cooling effect of green and water is modelled for urban areas, only areas with at least 20% sealed areas in a 1 km radius around a cell have been included in the map, using the intermediate map for $\%soil\ sealing_{1km}$ variable that is described in step 2.3 and imposing a minimum threshold of 20%.

5.3 This calculation results in the map 'Cooling effect of urban green and water'.

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 larger.

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.

4. References

De Ridder, K., and G. Schayes, 1997: The IAGL land surface model. J. Appl. Meteor., 36, 167–182.

De Ridder K., Lauwaet D., Maiheu B., 2015. UrbClim – a fast urban boundary layer climate model. Urban Climate, 12, 41-58.

Lauwaet D., Hooyberghs H., Maiheu B., Lefebvre W., Driesen G., Van Looy S., De Ridder K., 2015. Detailed Urban Heat Island projections for cities worldwide: dynamical downscaling CMIP5 global climate models. Climate, 3, 391-415.

Lauwaet D., De Ridder K., Saeed S., Brisson E., Chatterjee F., van Lipzig N.P.M., Maiheu B., Hooyberghs H., 2016. Assessing the current and future urban heat island of Brussels. Urban Climate, 15, 1-15.

Wieringa J., 1986. Roughness-dependent geographical information of surface wind speed averages. QJRMS, 112, 876-889.

Appendix

A1 Input and output file names

Table A 1 Names of input files

Input	File name	Source
Input map		
Wind speed	Wind_10m.asc	Royal Netherlands Meteorological Institute (KNMI)
Inhabitants	Inwoners.asc	RIVM
Land cover/ecosystem unit map 2013	LCEU kaart.shp	Statistics Netherlands (CBS)
Trees	Bomenkaart.tif	RIVM
Bushes and shrubs	Struikenkaart.tif	RIVM
Low vegetation	Graskaart.tif	RIVM
Vegetation cover	Groen_som.tif	VITO
Percentage non-green area	Perc_nietgroenkaart.tif	VITO
Look-up table		
Roughness length for momentum	Ruwheidslengte_LU.tab	De Ridder, K., and G. Schayes (1997)
UHI reduction	UHIreductie.tab	VITO
Soil sealing	Verhard.tab	VITO

A2 Script

fullarea.asc

```
//VERKOELING STAD - werkversie april 2017

//STAP 1: Laad de benodigde inputkaarten
assign(LCEU_ini,'LCEU_ini.tif')
assign(LCEU_ini_maskdata,if(or(isnodata(LCEU_ini),oreq(LCEU_ini,0,999)),0,1))

//groenkaarten
assign(boom,['bomenkaart.tif'])
assign(struik,['struikenkaart.tif'])
assign(gras,['graskaart.tif'])
assign(groen_som,'out/groen_som.tif')
assign(perc_nietgroenk,'out/perc_nietgroenkaart.tif')

//STAP 2: Windkaart aanpassen
assign(wind_10m,'out/wind_10m.asc')
assign(wind_10m_isdata,not(isnodata(wind_10m)))
assign(wind_10m,sumInBuffer(wind_10m,50,meter)/sumInBuffer(wind_10m_isdata,50,meter))
write('out/wind_10m_smooth.tif',wind_10m)
assign(wind_10m_isdata,not(isnodata(wind_10m)))

//Stap 3: Inschatting potentieel UHI
assign(inw_10km,'out/inw_10km.asc')
assign(maxUHI1,-1.605 + 1.062*log(inw_10km)/log(10) - 0.356*wind_10m)
//correctie: als maxUHI negatief of NoData owv inw=0, maar isdata LCEU_ini en wind_10m --> 0 ipv NoData
assign(maxUHI,if(or(lt(maxUHI1,0),and(isnodata(maxUHI1),LCEU_ini_maskdata, wind_10m_isdata)),0,maxUHI1))
write('out/maxUHI.tif',maxUHI)
assign(verhard, reclass('../kt/Verhard.tab', LCEU_ini))
assign(verhard_corr,if(verhard,verhard-(groen_som/100),verhard))
write('out/verhard_corr.tif', verhard_corr)
assign(verhard_1km,sumInBuffer(verhard_corr,1000,meter)/sumInBuffer(LCEU_ini_maskdata,1000,meter))
write('out/verhard_1km.tif',verhard_1km)
assign(potUHI, maxUHI*verhard_1km)
write('out/potUHI.tif',potUHI)

//STAP 4: Bepaal in situ effect verkoelend groen/blauw
assign(reductie_LU,reclass('../kt/UHIreductie.tab', LCEU_ini))
assign(reductie,boom/100*0.5+struik/100*0.3+gras/100*0.2+perc_nietgroenk/100*reductie_LU)
write('out/groenreductie.tif',reductie)
assign(groeneffect,potUHI*reductie)
write('out/Verkoelend_effect_van_groen.tif',groeneffect)

//STAP 5: Inschatting werkelijke UHI
assign(reductie_30m,sumInBuffer(reductie,30,meter)/sumInBuffer(LCEU_ini_maskdata,30,meter))
write('out/groenreductie_30m.tif', reductie_30m)
assign(UHI,potUHI*(1-reductie_30m))
write('out/UHI_30m.tif',UHI)

//STAP 6: Bepaal effect verkoelend groen/blauw
//Note: this step has not been scripted in GDX yet, has been carried out manually

exit
```