



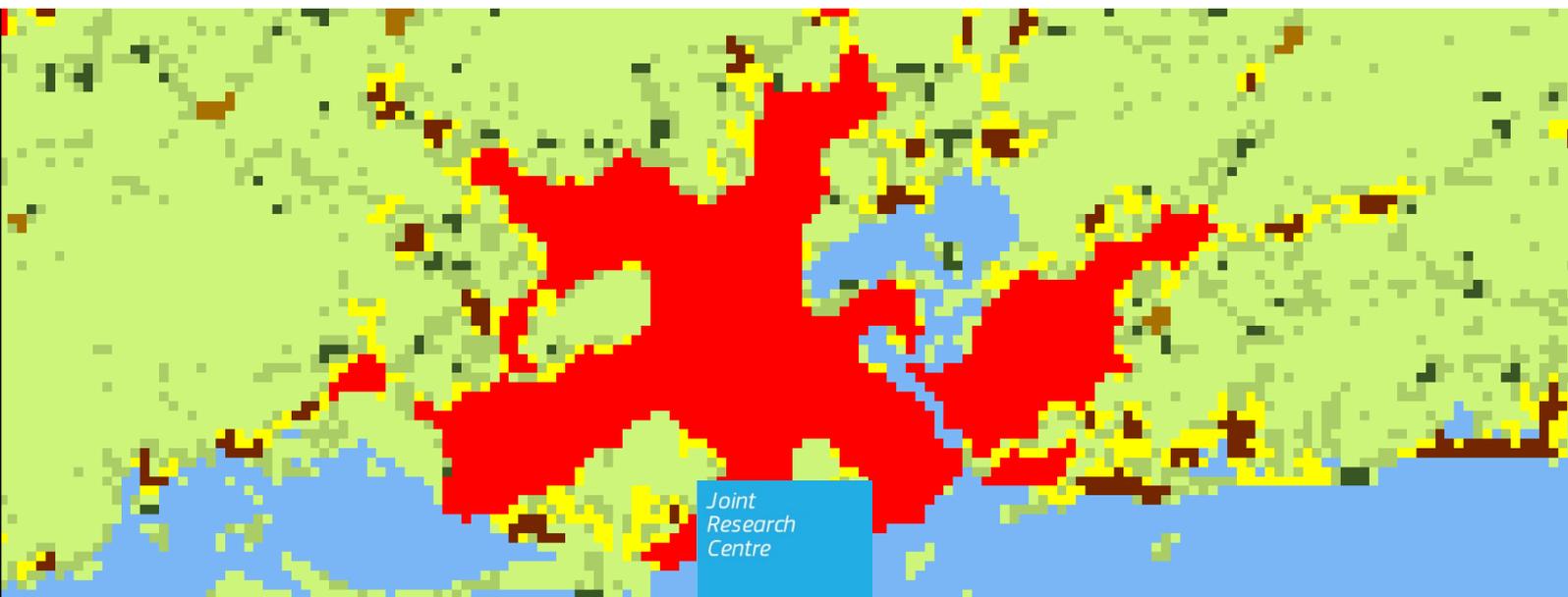
JRC SCIENTIFIC INFORMATION SYSTEMS AND DATABASES

DUG User Guide

*Degree of Urbanisation Grid
User Guide
Version 3.0*

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Abstract

The Degree of Urbanisation Grid (DUG) Tool (– version 3.0) is an information system developed in the framework of the Global Human Settlement Layer (GHSL) to produce geospatial grids to map settlement classes and extract related statistics. The settlement classes are derived from the “*Degree of Urbanisation*” method and ported to the GHSL environment through the *GHSL Settlement Mode (GHSL SMOD)*.

The DUG 3.0 is designed as a scalable tool allowing the application of the *GHSL Settlement Model* to the input data available to the user or to data made available in the GHSL Data Package 2019. This document contains the description of the DUG Tool use, the rationale of the differentiation between settlement classes and the comprehensive description of the outputs. The tool is a capacity enhancement asset in the framework of the multi-stakeholder effort to develop a people-based harmonised definition of cities and settlements that helps the assessment of the feasibility of applying a global definition of cities/urban areas in support of global monitoring of SDGs and the New Urban Agenda urban targets.

The DUG, as all GHSL Tools, is issued with an end-user licence agreement, included in the download package.

1 Introduction

The Global Monitoring Framework of the 2030 Agenda for Sustainable Development includes several indicators that require disaggregation in urban and rural classes, and several others that are sensitive to how an urban area is delineated. So far, however, no method or international standard has been proposed at the global level to delineate these areas. The broad array of different criteria applied in national definitions of rural-urban areas poses serious challenges to cross-country comparisons (ILO 2018). Both the Action Framework of the Implementation of the New Urban Agenda (UN-Habitat 2017) and the Global Strategy to improve Agricultural and Rural Statistics (GSARS 2018) highlight the need for a harmonised method to facilitate international comparisons and to improve the quality of rural and urban statistics in support of national policies and investment decisions.

Under these circumstances the European Union, The Food and Agriculture Organization of the United Nations (FAO), the International Labour Office (ILO), the Organisation for Economic Co-operation and Development (OECD), UN-Habitat and the World Bank have joined forces to develop a new method to delineate cities, urban and rural areas in a harmonised way. This work was launched at the Habitat III conference in 2016 with the explicit aim to organise global consultations and present the new method to the UN Statistical Commission for endorsement.

The goal is to facilitate international statistical comparisons of the performance of cities, urban and rural areas across a selection of global indicators. This method is meant to complement and not replace existing national definitions. National definitions typically rely on a much wider set of indicators and can be adjusted to take into account specific national characteristics. This richness makes national definitions more suitable for national policies, but less suitable for international or global comparisons.

The “*Degree of Urbanisation*” (DEGURBA) is a statistical classification method originally introduced by the European Commission, Directorate of Regional and Urban Policy and successively refined by the joint work of the EU, the Food and Agriculture Organization of the United Nations (FAO), the International Labour Office (ILO), the Organisation for Economic Co-operation and Development (OECD), UN-Habitat and the World Bank. The DEGURBA aims to identify the spatial extents of “Urban Centres”, “Urban Clusters” and “Rural Areas” based on resident population density grids at a scale (spatial detail or resolution) of 1 square kilometre (Dijkstra and Poelman 2014). Following the methodology indicated by the statistical office of the European Union (EUROSTAT), the population grids classified by the DEGURBA method can be used for statistical characterisation of local administrative units¹.

The *GHSL Settlement Model* (GHSL SMOD) is the porting of the DEGURBA in the Global Human Settlement Layer (GHSL) framework developed by the European Commission, Joint Research Centre². The GHSL SMOD supports the international multi-stakeholder discussion on the DEGURBA operationalization parameters and on the DEGURBA derived metrics and indicators using the GHSL baseline information as common global data frame (European Commission, Joint Research Centre 2018) (Melchiorri et al. 2018) (Corbane et al. 2018) (Melchiorri et al. 2019)

The “*Degree of Urbanisation Grid*” DUG 3.0 described in this report is a standalone free software tool incorporating the latest developments of the GHSL SMOD refining the DEGURBA classification in seven distinct settlement classes sub-characterizing at a second hierarchical level the urban cluster and the rural spatial domains of DEGURBA. The DUG 3.0 is designed as a scalable tool allowing the application of the GHSL SMOD method to the input data available to the user, at different optional input data complexity requirements, to generate at the second hierarchical level the settlement entities (Urban Centres, Dense Urban Clusters, Semi-Dense Urban Clusters and Rural Clusters) and the settlement classification grid documented in the GHSL Data Package 2019 (Florczyk et al. 2019).

¹ <https://ec.europa.eu/eurostat/web/degree-of-urbanisation/background>

² <https://ghsl.jrc.ec.europa.eu/>

1.1 GHSL Settlement model (GHSL SMOD)

The “Degree of Urbanisation Grid” DUG 3.0 generates output grids and spatial entities by classifying 1 km² grid cells, on the basis of population density, size and contiguity, with the GHSL SMOD classification schema organized in two separate hierarchical levels.

The mandatory input for the GHSL SMOD is a 1 km² population grid in selected coordinates systems (see section 4.1.1). Other sources may be optionally required accordingly to the number and the type of model operational assumptions as described in the paragraph 1.2. Each grid cell has the same shape and size, thereby avoiding distortions caused by using units varying in shape and size. This is a considerable advantage when compared to methods based on the population size and density of local administrative units.

At the first hierarchical level, the GHSL SMOD classifies the 1 km² grid cells by identifying the following spatial entities: a) “Urban Centre”, b) “Urban Cluster” and classifying all the other cells as “Rural Grid Cells”.

The basic criteria for the definition of the spatial entities at the first hierarchical level are:

- **“Urban Centre” (also “High Density Cluster” - HDC)** - An Urban Centre consists of contiguous grid cells (4-connectivity cluster) with a density of at least 1,500 inhabitants per km² (grid cell) and has at least 50,000 inhabitants in the cluster;
- **“Urban Cluster” (also “Moderate Density Cluster” - MDC)** - An Urban Cluster consists of contiguous grid cells (4-connectivity cluster) with a density of at least 300 inhabitants per km² (grid cell) and has at least 5,000 inhabitants in the cluster. By definition, the Urban Centres are subsets of the corresponding Urban Clusters.

The **“Rural grid cells” (also “Mostly Low Density Cells” - LDC)** are all the other cells that do not belong to an Urban Cluster. Most of these will have a density below 300 inhabitants per km² (grid cell); some may have a higher density, but they are not part of cluster with sufficient population to be classified as an Urban Cluster.

The settlement grid at level 1 represents these definitions on a layer grid. Each pixel is classified as follow:

- **Class 3: “Urban Centre grid cell”**, if the cell belongs to an Urban Centre;
- **Class 2: “Urban Cluster grid cell”**, if the cell belongs to an Urban Cluster and not to an Urban Centre;
- **Class 1: “Rural grid cell”**, if the cell does not belong to an Urban Cluster.

The second hierarchical level of the GHSL SMOD is a refinement of the DEGURBA set up to identify smaller settlements. It follows the same approach based on population density, population size and contiguity with a **nested classification** into the first hierarchical level. At the second hierarchical level, the GHSL SMOD classifies the 1 km² grid cells by identifying the following spatial entities: a) “Urban Centres” as at the first level; b) “Dense Urban Cluster” and c) “Semi-dense Urban Cluster” as parts of the “Urban Cluster”, classifying all the other cells of “Urban Clusters” as “Suburban or peri-urban grid cells”; and identifying d) “Rural Cluster” within the “Rural grid cells”. All the other cells belonging to the “Rural grid cells” are classified as “Low Density grid cells” or “Very Low Density grid cells” according to their cell population (Figure 1 and Table 1).

Here are reported the definition of the spatial entities at the second hierarchical level (Figure 1):

- **“Urban Centre” (also “Dense, Large Settlement”)** - An Urban Centre consists of contiguous grid cells (4-connectivity cluster) with a density of at least 1,500 inhabitants per km² (grid cell) and has at least 50,000 inhabitants in the cluster;
- **“Dense Urban Cluster” (also “Dense, Medium Cluster”)** - A Dense Urban Cluster consists of contiguous cells (4-connectivity cluster) with a density of at least 1,500 inhabitants per km² (grid cell) and has at least 5,000 and less than 50,000 inhabitants in the cluster;
- **“Semi-dense Urban Cluster” (also “Semi-dense, Medium Cluster”)** - A Semi-dense Urban Cluster consists of contiguous grid cells (4-connectivity cluster) with a density of at least 300 inhabitants per km² (grid cell), has at least 5,000 inhabitants in the cluster and is at least 3-km away from other Urban Clusters;
- **“Rural cluster” (also “Semi-dense, Small Cluster”)** - A Rural Cluster consists of contiguous cells (4-connectivity cluster) with a density of at least 300 inhabitants per km² (grid cell) and has at least 500 and less than 5,000 inhabitants in the cluster.

The **“Suburban or peri-urban grid cells” (also Semi-dens grid cells)** are all the other cells that belong to an Urban Cluster but are not part of a Urban Centre, Dense Urban Cluster or a Semi-dense Urban Cluster.

The **“Low Density Rural grid cells” (also “Low Density grid cells”)** are Rural grid cells with a density of at least 50 inhabitants per km² (grid cell) and are not part of a Rural Cluster.

The **“Very low density rural grid cells” (also “Very Low Density grid cells”)** are cells with a density of less than 50 inhabitants per km² (grid cell).

Optionally the GHSL SMOD classifies as **“Water grid cells”** all the cells with more than 0.5 share covered by permanent surface water that are not populated nor built.

The settlement grid at level 2 represents these definitions on a single layer grid. Each pixel is classified as follow (**Error! Reference source not found.**):

- **Class 30: “Urban Centre grid cell”**, if the cell belongs to an Urban Centre spatial entity;
- **Class 23: “Dense Urban Cluster grid cell”**, if the cell belongs to a Dense Urban Cluster spatial entity;
- **Class 22: “Semi-dense Urban Cluster grid cell”**, if the cell belongs to a Semi-dense Urban Cluster spatial entity;
- **Class 21: “Suburban or per-urban grid cell”**, if the cell belongs to an Urban Cluster cells at first hierarchical level but is not part of a Dense or Semi-dense Urban Cluster;
- **Class 13: “Rural cluster grid cell”**, if the cell belongs to a Rural Cluster spatial entity;
- **Class 12: “Low Density Rural grid cell”**, if the cell is classified as Rural grid cells at first hierarchical level, has more than 50 inhabitant and is not part of a Rural Cluster;
- **Class 11: “Very low density rural grid cell”**, if the cell is classified as Rural grid cells at first hierarchical level, has less than 50 inhabitant and is not part of a Rural Cluster;
- **Class 10: “Water grid cell”**, if, with given settings (see section 1.2), the cell has 0.5 share covered by permanent surface water and is not populated nor built.

Figure 1. Schematic overview of GHSL SMOD entities workflow logic. “xpop” represents the population density per grid cell; “xbu” represents the built-up density per grid cell.

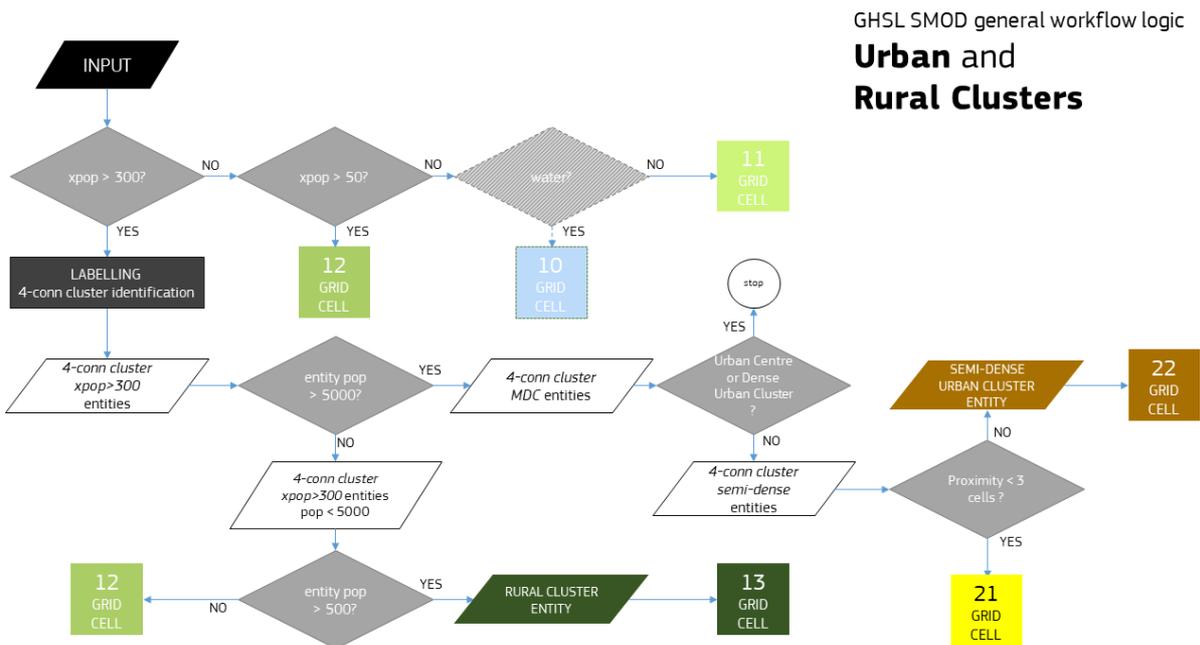
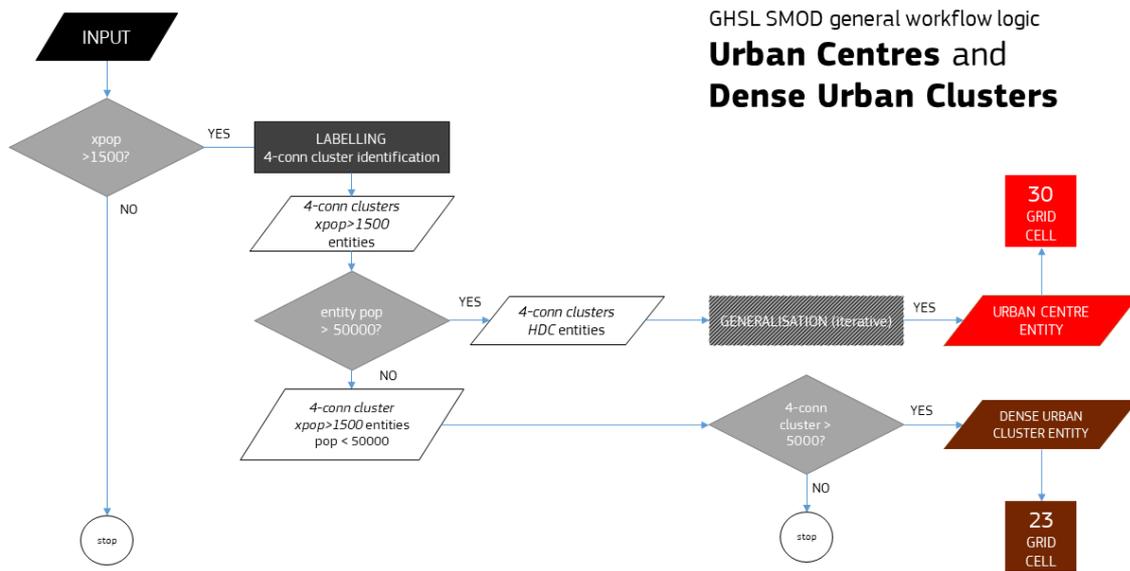
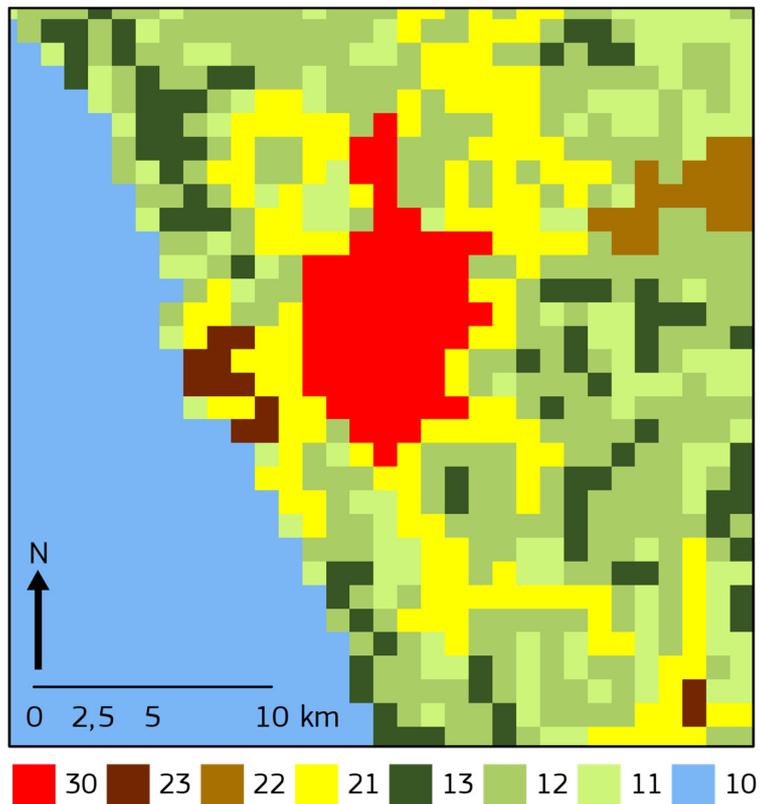


Table 1 Logic of the GHSL SMOD second hierarchical level

| | | Minimum population size of the cluster of cells (settlement size) | | | No minimum population size criterion (not an entity) |
|--|------------|---|--------------------------|---------------|--|
| | | >50,000 | 50,000 - 5,000 | 5,000 - 500 | |
| Population density of cells, inhabitants per km ² | >1500 | Urban Centre | Dense Urban Cluster | Rural Cluster | |
| | 300 - 1500 | | Semi-Dense Urban Cluster | | Suburban or peri urban grid cells |
| | 300 - 50 | | | | Low Density Rural grid cells |
| | <50 | | | | Very Low Density Rural grid cells |

Figure 2 Output of the GHSL SMOD implemented by the DUG 3.0 in the north of Malaysia displaying settlement class per grid cell



1.2 Options description

The *GHSL Settlement Model* (GHSL SMOD) included in the “*Degree of Urbanization Grid*” DUG 3.0 software operates in seven optional modalities **01 to 07**, ordered from low to high number of model assumptions and necessary input data complexity. This approach was designed in order to provide a scalable solution able to support different user requirements and to operate in different and non-GHSL data ecosystems not necessarily compliant with the GHSL data technical specs and quality control procedures. The seven distinct operative model assumptions are listed below with a short description.

- (1) Basic criteria (local population densities: 50, 300 and 1500; 4-connectivity cluster rule; cluster population size: 500, 5K, 50K)** – they are the basic criteria shaping the GHSL Settlement model (as in the DEGURBA method) as grid population density, grid cluster population size, and connectivity rule to form grid cell clusters they are valid for all the options (such basic criteria are the ones described in the entities definitions of paragraph 1.1; Table 1, **Error! Reference source not found.** and Figure 1).
- (2) Permanent water surface excluded** – under this assumption, all cells with at least 0.5 share of permanent water surface not populated nor built, are classified as “Water grid cells”, to exclude from the settlement classification at the second hierarchical level areas that are not on land.
- (3) Density on permanent land** – under this assumption, the densities values used in the GHSL SMOD are calculated using the permanent land surface portion inside the unitary surface of the spatial unit (grid cell) rather than the total unitary surface of the spatial unit (grid cell). The effect is to mitigate the blurring effect of the SMOD operations performed at scale of 1x1 kilometres particularly evident in case of sharp urban edges as for example in coastal cities. As example, under this assumption the Urban Centre class definition is set as following: “An Urban Centre consists of contiguous grid cells (4-connectivity cluster) with a density of at least 1,500 inhabitants per km² of permanent land and has at least 50,000 inhabitants in the cluster”. Similarly, for all the other GHSL SMOD classes set by density cut-off values.
- (4) xbu_share 50%** – under this assumption, the Urban Centres are set by the following definition: “An Urban Centre consists of contiguous grid cells (4-connectivity cluster) with a density of at least 1,500 inhabitants per km² of permanent land or with a share of built-up surface greater than 0.5 of permanent land, and has at least 50,000 inhabitants in the cluster”. This assumption is useful for accommodating the presence in the city of large areas with low resident inhabitants but strongly functionally linked with the city, as for example large productive or commercial areas (typical case of cities in Unites States of America). As for consistency with the basic criteria rule of full containment of Urban Centres into Urban Clusters also the definition of Urban Cluster is extended as follow
- (5) Generalization of HDC (smooth and gap filling)** – under this assumption, the cluster of the Urban Centre set by the density cut-off value it is spatially generalized by iterative majority filtering process done with a kernel of 3x3 kilometres until idempotence it is reached. Moreover, the remaining holes within the Urban Centre perimeter after the smoothing are filled if they are smaller than 15 km² in surface. The effect of this assumption is that Urban Centres as derived from the input GRIDS are more compact and simple in shape, then easier to translate to GIS POLYGON entities. The cost of the generalization is that sample units (grid cells) that may violate the “Urban Centre” logical assumptions regarding densities values are included in the “Urban Centre” domain. Ideal typical case is the inclusion of large parks (less than 15 km²) or low-density population areas within the “Urban Centre” perimeter because completely surrounded by GRID samples with high density belonging to the “Urban Centre” class. Under this assumption the Urban Centre class definition is set as following: “An Urban Centre consists of contiguous grid cells (4-connectivity cluster) with a density of at least 1,500 inhabitants per km² of permanent land or with a share of built-up surface greater than 0.5 of permanent land, and has at least 50,000 inhabitants in the cluster **with smoothed boundaries and <15 km² holes filled**”.
- (6) xbu_share 3%** – under this assumption, candidate samples for the “Urban Cluster” domain are accepted only if they exhibit a built-up surface share greater than 0.03. Grid cells are included in the urban cluster domain only if some minimal evidences of physical built-up structure was recorded by an independent source respect to census data. The GHSL SMOD rule set for the urban cluster domain consequently become: “An Urban Cluster consists of contiguous grid cells (4-connectivity cluster) with a density of at least 300 inhabitants per km² of permanent land, **a built-up share greater than 0.03 of permanent land and has at least 5,000 inhabitants in the cluster**”. The purpose of this option is to increase the robustness of the GHSL SMOD response by forcing consistency between census-derived sources (population grids) and

land cover / land use sources (built-up areas) mitigating the effect of misalignment, thematic bias, scale gaps or other data gaps that may be present in the data.

(7) Impose national boundaries - under this assumption, the single urban entity (urban centre or urban cluster) exists only inside the given country boundary. Consequently, the rule set for the urban centre will become the following: “An Urban Centre consists of contiguous grid cells (4-connectivity cluster) **inside the same country border**, with a density of at least 1,500 inhabitants per km² of permanent land or with a share of built-up surface greater than 0.5 of permanent land, and has at least 50,000 inhabitants in the cluster with smoothed boundaries and <15 km² holes filled **within the country border**”. Similarly, for all the other GHSL SMOD entities. A given cluster of GRID cells fitting the population density criteria may be one single urban centre across two different countries. If split under this assumption in two clusters, both of them may match the size criteria of 50,000 inhabitants in the cluster and then become two urban centres, or only one of them, or none of them, depending on the total size of the cluster and on the way this is cut by the country border.

Table 2 shows schematically the GHSL SMOD operationalization assumptions in place for the different GHSL SMOD options (option code). They are organized using an increasing hierarchical approach (1 to 7). At the GHSL SMOD option O1, only the basic assumption (1) is in place, while at SMOD option O7, the model works with the whole set of assumptions from (1) to (7).

Increasing number of model assumptions requires increasing number of data sources necessary to apply the GHSL SMOD model. The mandatory data sources at the GHSL SMOD option O1 is the population grid XPOP. Other data sources are necessary optionally if higher GHSL SMOD option code are selected from O2 to O7. Data to be included in the higher options are also progressively listed in the Table 2 below.

Table 2 GHSL SMOD operationalization Assumptions and Optional Codes (green markers identify assumptions in place per each option code, red markers the ones not in place)

| Option Code | basic criteria (300, 1500, 4-conn 5K, 50K) | permanent water surface excluded | density on permanent land | xbu_share 50% | generalization of HDC (smooth, gap filling) | xbu_share 3% | impose national boundaries |
|----------------|--|----------------------------------|---------------------------|------------------|---|------------------|----------------------------|
| 01 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 02 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 03 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 04 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 05 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 06 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 07 | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Required Input | XPOP | XPOP, XLAND | XPOP, XLAND | XPOP, XLAND, XBU | XPOP, XLAND, XBU | XPOP, XLAND, XBU | XPOP, XLAND, XBU, Xcountry |

Note:

X_{POP}: GIS GRID reporting about resident population counts per 1 km² grid cell

X_{LAND}: GIS GRID reporting about the share of 1 km² grid cell covered by permanent land surface

X_{BU}: GIS GRID reporting about the share of the 1 km² grid cell covered by built-up area surface

X_{COUNTRY}: GIS POLY/GRID reporting about country borders

2 Installation

2.1 System requirements

The Degree of Urbanisation Grid (DUG) is graphical tool developed in MATLAB and created for Windows, its system requirements are listed below (Table 3)

Table 3. System requirements

| Requirements | Operating system | Processor | RAM | Disk space |
|--------------|------------------|-----------------------------------|-------|--------------------------------------|
| Minimum | Windows 7 | Any Intel or AMD x86-64 processor | 6 GB | 150 Mb (+ 700 Mb for Matlab Runtime) |
| Recommended | Windows 10 | Any Intel or AMD x86-64 processor | 16 GB | 150 Mb (+ 700 Mb for Matlab Runtime) |

DUG operates on raster grids: the larger the grid the higher the required memory. Few examples of RAM requirements in the most computational expensive scenario are below in Table 4. The input raster size (in number of 1 km grid cells) is intended per each of the raster layer(s).

Table 4. Requirements by input raster size

| Input rasters size | RAM needed | Disk space for outputs |
|--------------------|------------|------------------------|
| 1000x1000 pixels | 6 GB | < 10 MB |
| 5000x5000 pixels | 12 GB | < 50 MB |

2.2 Installation procedure

2.2.1 Install MATLAB Runtime

DUG is developed in MATLAB and the MATLAB Runtime is required to run the tool.

The specific version to be installed is **R2018b (9.5)**, Windows 64-bit version.

Check for the official MATLAB website to download and install:

<https://it.mathworks.com/products/compiler/matlab-runtime.html>

2.2.2 Install DUG

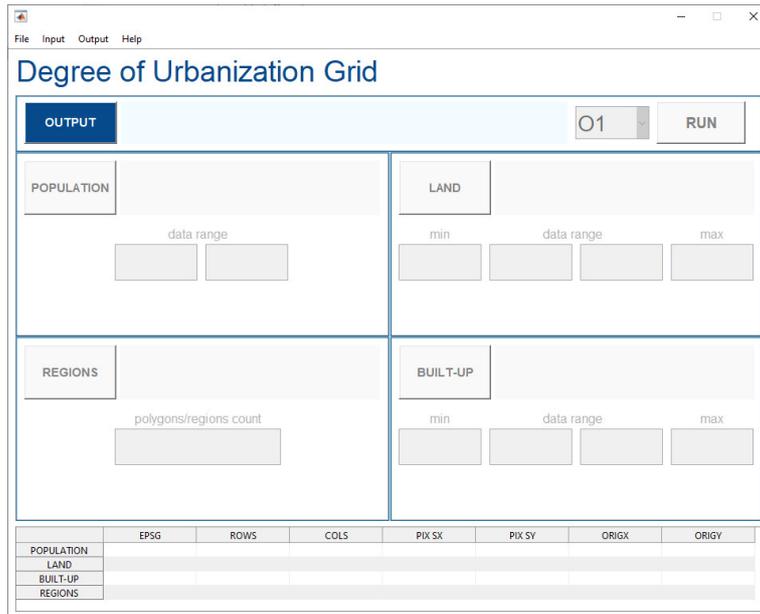
Once the MATLAB Runtime is installed, if you have not done so already, download the DUG 3.0 tool from the GHSL website (Tools section):

<https://ghsl.jrc.ec.europa.eu/tools.php>

Unzip the DUG.zip file and run the executable directly by double click the *DUG.exe* file.

N.B. The first time DUG is launched on a new computer it performs several checks and initialization steps, therefore it can take up to 2 minutes to start.

Figure 3. First startup



2.2.3 Remove DUG

To uninstall DUG simply delete the entire folder containing the *DUG.exe* file.

MATLAB Runtime can also be removed if not necessary for other applications.

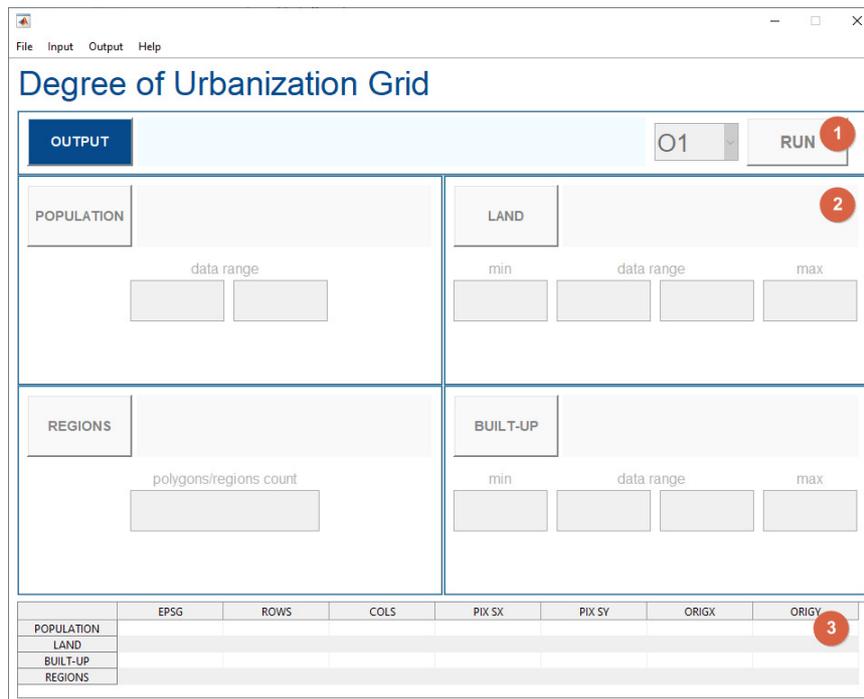
3 The graphical user interface

The DUG graphical user interface is created in MATLAB and distributed as a standalone application.

The main window is divided in three areas:

1. Top panel, which contains the buttons to select the output folder, choose the GHSL SMOD option code to compute and start the process;
2. Middle panel, which contains four areas in a 2x2 grid, which allow to select the input layers: population, land, built-up area and region data;
3. Bottom panels, which display basic spatial/control information about the input data (e.g. EPSG, raster size in pixels, etc.).

Figure 4. DUG main windows and areas



Not all areas are active for all option codes: depending on the GHSL SMOD to compute, some inputs are not required and therefore the corresponding area is disabled.

After the start, the user is guided in the process of input selection, starting from the output folder, continuing with the population raster and the other grids depending on the chosen GHSL SMOD option code.

3.1 Menu bar

The menu bar is organized as in four sections:

1. File
2. Input
3. Output
4. Help

3.1.1 File menu

Table 5. File menu bar

| Item | Action | Shortcut |
|-------------|------------------------------------|-----------------|
| Run | Starts the GHSL SMOD computation | CTRL + R |
| Quit | Exit DUG and close the main window | CTRL + Q |

3.1.2 Input

Table 6. Input menu bar

| Item | Action | Shortcut |
|-------------|---|-----------------|
| Population | Select and load the Population grid | CTRL + P |
| Land | Select and load the Land grid | CTRL + L |
| Built-up | Select and load the Built-up area grid | CTRL + B |
| Regions | Select and load the Regions file (grid or vector) | CTRL + N |

3.1.3 Output

Table 7. Output menu bar

| Item | Action | Shortcut |
|-------------|-----------------------|-----------------|
| Output | Set the output folder | CTRL + O |

3.1.4 Help

Table 8. Help menu bar

| Item | Action | Shortcut |
|-------------|---|-----------------|
| Online help | Open a web page to the DUG documentation website using the default browser | CTRL + H |
| About DUG | Open a new window containing DUG version number, release date and contact information | |

3.2 Buttons

All buttons are located in the top and the middle panels in the main window. Some of them provide the same functionality of the single menu entries and are an alternative way to set input data and start the GHSL SMOD computation.

Table 9. Buttons

| Item | Action | Shortcut |
|-------------|---|----------|
| OUTPUT | Set the output folder | CTRL + O |
| OPTION CODE | Choose the GHSL SMOD to compute, from O1 to O7 | |
| RUN | Starts the GHSL SMOD computation | CTRL + R |
| POPULATION | Select and load the Population grid | CTRL + P |
| LAND | Select and load the Land grid | CTRL + L |
| BUILT-UP | Select and load the Built-up area grid | CTRL + B |
| REGIONS | Select and load the Regions grid or vector file | CTRL + N |

3.3 Editable text fields

The land and built-up area panels contain two editable text field that allow the user to setup the expected minimum and maximum value of the input data. These values are used to rescale the input data in the range 0 - 1 in order to have normalized data before starting the GHSL SMOD computation.

The expected min and max values are precomputed internally, but can be adjusted by the user in case the heuristic guessed a wrong value.

Box 1. Example of rescaling

The input built-up layer should range 0 to 100. If the user built-up area raster contains values ranging, for example, from 0 to 80 (see Figure 12), DUG heuristic choose 0 and 100 as minimum and maximum possible values. If the real maximum value is 80 instead, e.g. 80 means 100% built-up, the user must change it and then rescaling will be performed from 0 to 80 instead of 0 to 100.

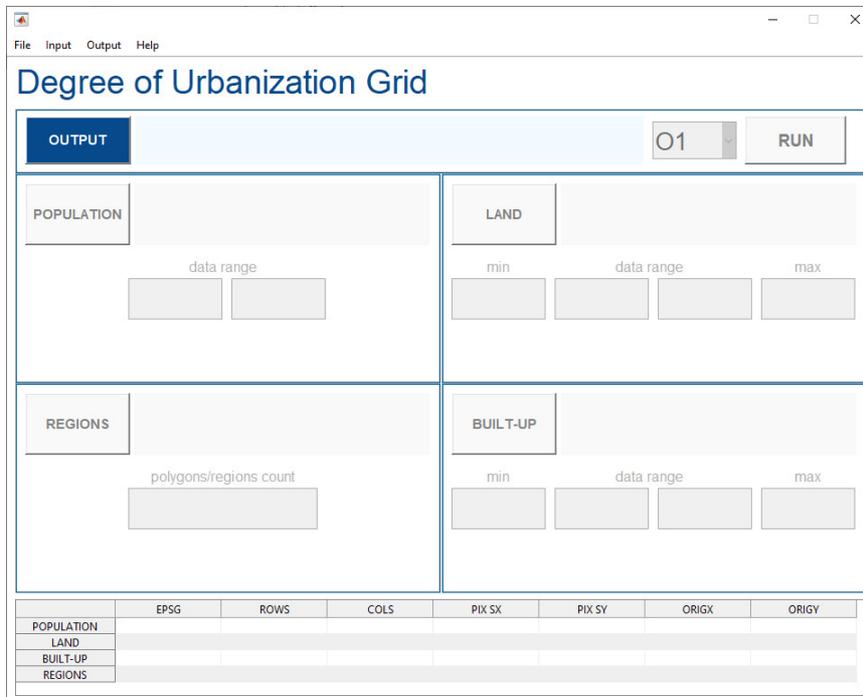
Table 10. Editable text fields

| Item | Action |
|--------------|--|
| Land min | Set all land pixels that are less than the specified value to this value before scaling |
| Land max | Set all land pixels that are more than the specified value to this value before scaling |
| Built-up min | Set all built-up area pixels that are less than the specified value to this value before scaling |
| Built-up max | Set all built-up area pixels that are more than the specified value to this value before scaling |

3.4 Guided run

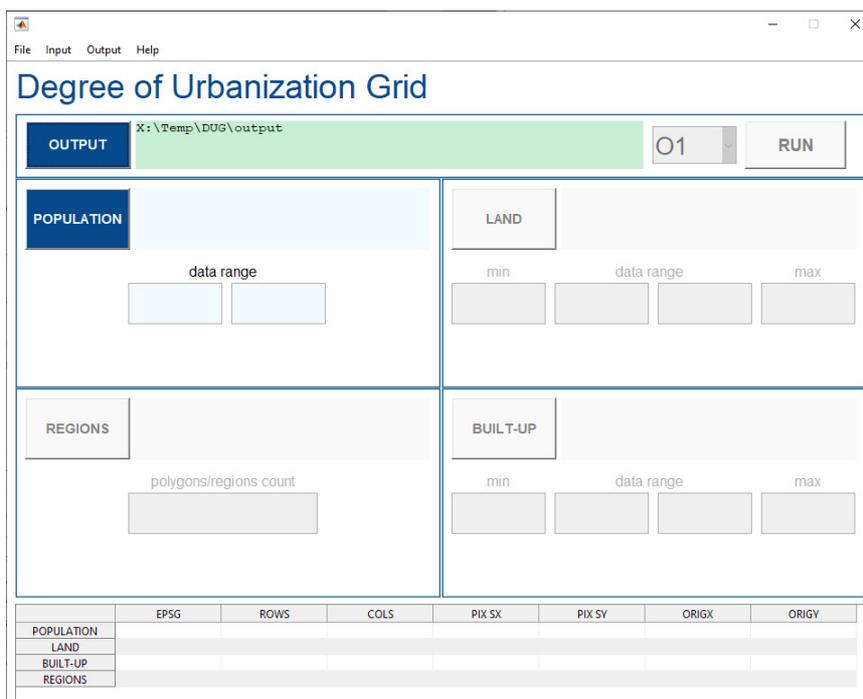
After starting DUG, the only active command is the output button (Figure 5): this is to set the output folder (path) first in order to create the log file and check disk write permission for results. Below in the shaded italic text lines the actions and commands the user should prompt to run the DUG Tool.

Figure 5. DUG startup



The user clicks on OUTPUT and selects the output folder. (Figure 6)

Figure 6. Output folder selected



Once output is set, the POPULATION become active.

The user chooses the population raster. (Figure 7)

Figure 7. Population selected

| | EPSG | ROWS | COLS | PIX SX | PIX SY | ORIGX | ORIGY |
|------------|------|------|------|--------|--------|--------|---------|
| POPULATION | 3035 | 4367 | 5585 | 1000 | -1000 | 943000 | 5308000 |
| LAND | | | | | | | |
| BUILT-UP | | | | | | | |
| REGIONS | | | | | | | |

Once population is set, minimum and maximum raster value are displayed in data range. Geographic info (EPSG, origin, etc) are shown in the table at the bottom.

Now the user can change the Option Code or click the RUN button, since SMOD 01 requires only population data.

Regions can also be loaded using the REGIONS button, in form of raster or shapefile: with O1 to O6 it will be used only to compute statistics in every distinct area.

Selecting an Option Code different the O1 will activate the land and/or the built-up area panels (Error! Reference source not found.).

The user can load the land and built-up area rasters as already done for the population.

Figure 8. Option Code O6 selected

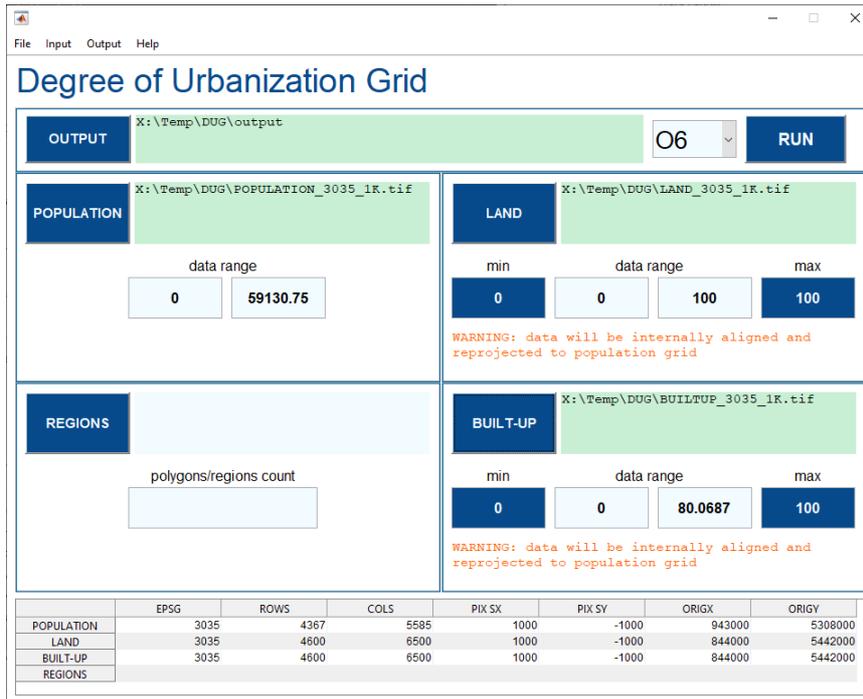
| | EPSG | ROWS | COLS | PIX SX | PIX SY | ORIGX | ORIGY |
|------------|------|------|------|--------|--------|--------|---------|
| POPULATION | 3035 | 4367 | 5585 | 1000 | -1000 | 943000 | 5308000 |
| LAND | | | | | | | |
| BUILT-UP | | | | | | | |
| REGIONS | | | | | | | |

Once land and/or built-up rea is loaded, minimum and maximum raster values are displayed in the data range. Geographic info (EPSG, origin, etc) are shown in the table at the bottom.

In case the rasters do not perfectly align (e.g. different projection or extent) a warning is displayed, to let the user know that the tool will internally re-projects those data, a sign of the transformation is compiled in the log file.

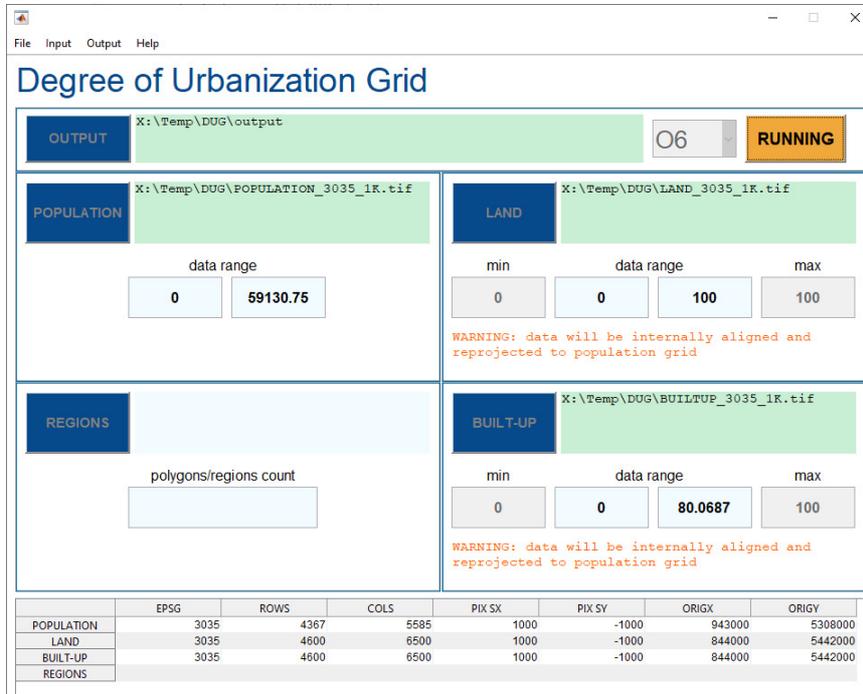
Internal heuristics set also the expected minimum and maximum value used to rescale the data, these values can be changed by the user (blue rectangles can be edited, limits are set as 0 – 100 for the example in Figure 9)

Figure 9. Land and Built-up rasters selected



All commands are disabled when running, the RUN button becomes orange with label RUNNING and the mouse pointer transform into wheel (Figure 10). Once the run completed everything is reactivated again.

Figure 10. DUG running



4 Input and output

4.1 Input

The input files requested by the tool depend on the selected GHSL SMOD Option Code (Table 11).

Table 11. Required input (marked by green squares) and optional input (hollow) by Option Code

| Input | 01 | 02 | 03 | 04 | 05 | 06 | 07 |
|--------------------|----|----|----|----|----|----|----|
| Population grid | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Land grid | | ■ | ■ | ■ | ■ | ■ | ■ |
| Built-up area grid | | | | ■ | ■ | ■ | ■ |
| Regions | □ | □ | □ | □ | □ | □ | ■ |

The Regions file is mandatory for Option Code 07 but also optional for all other Option Codes (to disaggregate statistics –see sub-section 4.2.2 p. 24).

The population has to meet key requirements, see all details in the Population grid sub-paragraph (4.1.1).

The land, built-up area and regions grids can instead be in any projection supported by GDAL (box 2 for details) and can have any pixel size. If those values do not match with the values from the population grid, those grids will be resampled and re-projected in order to align them to the population raster. A sign of the transformations is compiled in the log file. If transformation occurs, it takes place with the "Nearest Neighbor" resampling method, and the pixel resolution is 1 km by 1 km.

Box 2. Supported projections

Check the projection supported by DUG through GDAL at:

<https://proj.org/operations/projections/index.html>

4.1.1 Population grid

The population grid is the mandatory input to compute GHSL SMOD for all Option Codes. The population grid has to be a GeoTIFF file, with integer or float data type, in one among World Mollweide, LAEA Europe, or UTM zones projection, and with a 1 km x 1 km pixel size (Table 12). Each pixel shall contain the population count expressed as absolute number (e.g. "3125.9" means 3125.9 people). If the input population grid does not comply with these requirements the process cannot start and the tool throws an error. In such case the user needs to re-project and/or resample the grid in order to comply with these requirements or provide another grid. The re-projection of geospatial layers requires specific technical knowledge. No responsibility is taken for workflows performed by users.

Be careful: re-projecting population grid is a sensitive task, as the resampling method can affect population distribution and total count.

Table 12. Population grid requirements

| File format | Data type | Projection | Pixel size |
|-------------|----------------------------|---|-------------|
| GeoTIFF | Any numeric (int or float) | <ul style="list-style-type: none"> — World Mollweide (EPSG:54009) — ETRS89 / LAEA Europe (EPSG:3035) — UTM zones | 1 km x 1 km |

4.1.2 Land grid

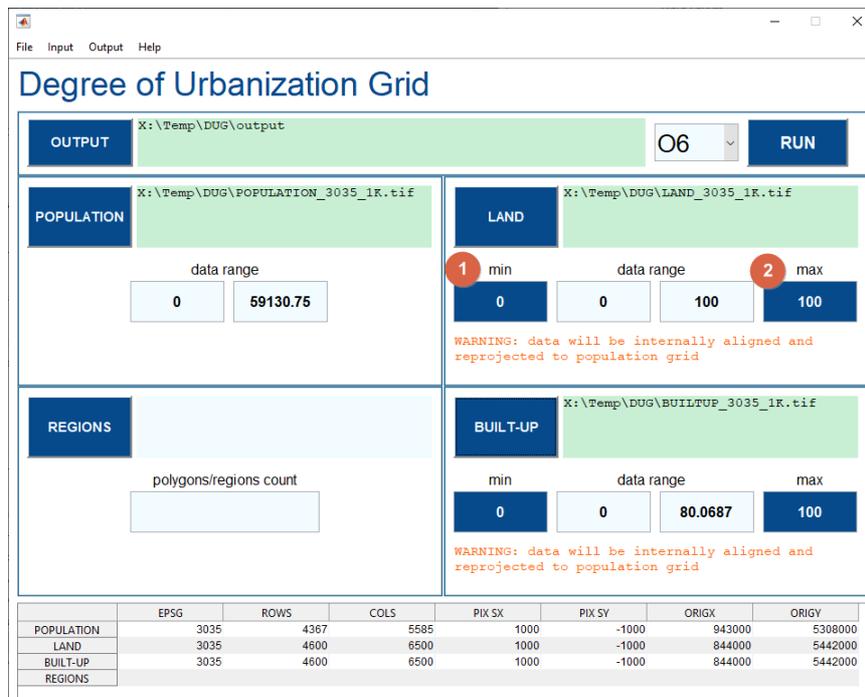
The land grid is mandatory for Option Codes 02, 03, 04, 05, 06 and 07, the characteristics of the layer are displayed in Table 13 below. The layer is expected to contain the pixel share of permanent land surface, usually expressed as a value in the range 0 - 1: "0" means 0% land, "1" means 100% land. The user can provide a grid with a different data range: in this case the tool will internally rescale those value to the standard range 0 - 1.

Table 13. Land grid requirements

| File format | Data type | Projection | Pixel size |
|-------------|----------------------------|---|--|
| GeoTIFF | Any numeric (int or float) | Any supported by GDAL, it will be reprojected to population's coordinate system | Any, it will be resized at 1 km x 1 km |

Once the land grid is loaded, its actual value range is displayed and the expected minimum and maximum values are guessed by the internal heuristics. The user can change these values to rescale the land grid using a different minimum and maximum values (operating on buttons highlighted with marker 1 and 2 in Figure 11).

Figure 11. Land grid expected min and max



Built-up area grid

The built-up area grid is required for Option Codes 04, 05, 06 and 07 the characteristics of the layer are displayed in Table 14. The built-up area grid shall contain the pixel share of built-up area, usually expressed as a value in the range 0 - 1: "0" means 0% built-up area, "1" means 100% built-up area. The user can provide a grid with a different data range: in this case the tool will internally rescale those value to the standard range 0 - 1.

Table 14. Built-up area grid requirements

| File format | Data type | Projection | Pixel size |
|-------------|----------------------------|--|--|
| GeoTIFF | Any numeric (int or float) | Any supported by GDAL, it will be reprojected to population's projection | Any, it will be resized at 1 km x 1 km |

Once the built-up area grid is loaded, its actual value range is displayed and the expected minimum and maximum values are guessed by the internal heuristics. The user can change these values to rescale the land grid using a different minimum and maximum values (operating on buttons highlighted with marker 1 and 2 in Figure 12).

Figure 12. Built-up area expected min and max

| | EPSG | ROWS | COLS | PIX SX | PIX SY | ORIGX | ORIGY |
|------------|------|------|------|--------|--------|--------|---------|
| POPULATION | 3035 | 4367 | 5585 | 1000 | -1000 | 943000 | 5308000 |
| LAND | 3035 | 4600 | 6500 | 1000 | -1000 | 844000 | 5442000 |
| BUILT-UP | 3035 | 4600 | 6500 | 1000 | -1000 | 844000 | 5442000 |
| REGIONS | | | | | | | |

4.1.3 Regions

The regions file has two purposes: it is mandatory for Option Code 07 to impose national boundaries (see point 7 in section 1.2); it is optional for all the other Option Codes to delineate the zones in which the tool computes the GHSL SMOD values and their statistics. These areas could be of any sort bigger than 1 grid cell (administrative areas, countries, major regions of the world). The regions file can be in the form of raster grid or vector data (all the characteristics of the regions file are presented in the following subsections).

4.1.3.1 Raster grid

The regions raster grid shall contain integer values: 0 is considered as the background or no region. All positive values are considered as distinct areas.

Table 15. Regions raster grid requirements

| File format | Data type | Projection | Pixel size |
|--------------------|----------------------------|---|--|
| GeoTIFF | Any numeric (int or float) | Any supported by GDAL, it will be re-project to population's projection | Any, it will be resized at 1 km x 1 km |

4.1.3.2 Polygons vector data

The regions file can be also provided in the shapefile format. In this case it will be internally rasterized using the population grid as target grid. Each polygon will get a unique identifier, ranging from 1 to the maximum number of polygons. DUG will also read the polygons attribute table and create a new sheet that combine these values with the GHSL SMOD statistics computed for each polygon.

Table 16. Regions vector file requirements

| File format | Data type | Projection | Geometry |
|--------------------|----------------------------|---|-----------------|
| Shapefile | Any numeric (int or float) | Any supported by GDAL, it will be re-project to population's projection | Polygons |

4.2 Output

The DUG 3.0 tool generates two types of output. First, the geospatial outputs, a combo of raster and shapefile layers that classify grid cells into settlement classes (as described in section 1.1 p.4) or delineate settlement entity. Second, the statistics including population count and areal extent per settlement class.

4.2.1 DUG geospatial output

The GHSL SMOD geospatial output data consists in several files. The following outputs are produced both as raster grid (GeoTIFF) and shapefile: Urban Centre entities, Dense Urban Cluster entities, Semi Dense Urban Cluster entities, and Rural Cluster entities; the settlement grid at second hierarchical level is delivered as raster grid (Table 17).

Table 17. DUG output files (outputs available marked in green)

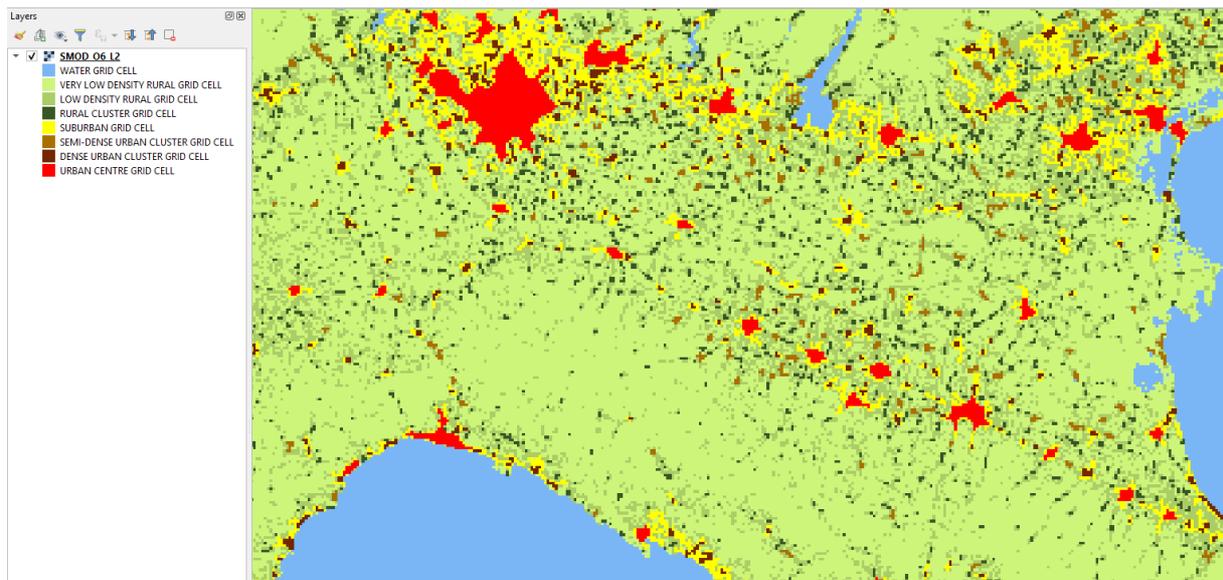
| Output | Raster | Shapefile |
|------------------------------|--------|-----------|
| DUG GRID L2 | ■ | |
| DUG URBAN CENTRE | ■ | ■ |
| DUG DENSE URBAN CLUSTER | ■ | ■ |
| DUG SEMI DENSE URBAN CLUSTER | ■ | ■ |
| DUG RURAL CLUSTER | ■ | ■ |

4.2.1.1 GHS-SMOD GRID L2

The GHSL SMOD raster file contains the DUG grid L2 classification, where each pixel is classified in one of these settlement classes: 10, 11, 12, 13, 21, 22, 23, 30 (see paragraph 1.1).

The filename of the output is *DUG_O{X}_GRID_L2.tif* (with X from 1 to 7 corresponding to the selected option code).

Figure 13. Screen capture of a QGIS session displaying the DUG Grid L2 output of the DUG tool. Example in northern Italy



4.2.1.2 DUG spatial entities

The DUG vector files contain spatial entities that are derived from GHSL SMOD grid L2 classification raster. The results are stored in shapefiles, where each entity has a unique identifier ranging from 1 to the maximum number of entities. The attribute table of the shapefile contains basic statistics (Table 18). See paragraph 4.2.2.3 for more information about the statistics stored into the entity shapefiles.

Table 18. GHSL SMOD spatial entities

| GHS-SMOD spatial entity | Shapefile filename | Shapefile statistics |
|--------------------------|---------------------------------------|--|
| URBAN CENTRE | DUG_O(X)_URBAN_CENTRE.shp | Area, population, built-up area ⁽¹⁾ |
| DENSE URBAN CLUSTER | DUG_O(X)_DENSE_URBAN_CLUSTER.shp | Area, population, built-up area ⁽¹⁾ |
| SEMI DENSE URBAN CLUSTER | DUG_O(X)_SEMI_DENSE_URBAN_CLUSTER.shp | Area, population, built-up area ⁽¹⁾ |
| RURAL CLUSTER | DUG_O(X)_RURAL_CLUSTER.shp | Area, population, built-up area ⁽¹⁾ |

⁽¹⁾ Only when built-up area grid is provided by the user

4.2.2 DUG output statistics

4.2.2.1 Global DUG statistics

DUG computes basic statistics about the generated DUG raster, representing population counts per each GHSL SMOD class (Population_count in Figure 14), number of grid cells per class (Area_km2), and the share of the total population accounted in each GHSL SMOD class (Population_share³). The input for the statistics is the raster grid *DUG Grid L2* output. The same statistics are also aggregated at the first hierarchical level without generating any additional raster (Figure 15)

Figure 14. Screen capture of a MS Office Excel session displaying an example of DUG L2 global statistics

| | A | B | C | D |
|---|----------|------------------|----------|------------------|
| 1 | L2_class | Population_count | Area_km2 | Population_share |
| 2 | 10 | 0 | 37948 | 0 |
| 3 | 11 | 898054.9227 | 407999 | 0.033099738 |
| 4 | 12 | 4707707.131 | 34161 | 0.173512629 |
| 5 | 13 | 3531490.086 | 4626 | 0.130160631 |
| 6 | 21 | 1956236.935 | 2438 | 0.072101302 |
| 7 | 22 | 807628.1617 | 778 | 0.029766866 |
| 8 | 23 | 3664146.405 | 978 | 0.135049964 |
| 9 | 30 | 11566520.1 | 1709 | 0.426308871 |

³ The population share represents the ratio between the selected class and the total sum of population in each class. Its value is in the range 0 - 1.

Figure 15. Screen capture of a MS Office Excel session displaying an example of DUG L1 global statistics

| | A | B | C | D |
|---|----------|------------------|----------|------------------|
| 1 | L1_class | Population_count | Area_km2 | Population_share |
| 2 | 1 | 9137252.14 | 484734 | 0.336772998 |
| 3 | 2 | 6428011.502 | 4194 | 0.236918131 |
| 4 | 3 | 11566520.1 | 1709 | 0.426308871 |

The filenames are DUG_O{X}_L2_stats.xls and DUG_O{X}_L1_stats.xls (with X from 1 to 7).

4.2.2.2 Statistics by region

When a region file is provided, then the population count per GHSL SMOD class is also disaggregated per region (Figure 16). Depending on the extent of the regions the total sum per class can be different than the one computed on the entire raster: if the regions area covers a smaller extent compared to the population grid input, statistics will be computed within the sole regions extent.

In the case the region file is a vector file, these statistics are also combined with the original shapefile attributes table. The table structure is straightforward, the population counts per class are organised in columns with the header containing the corresponding GHSL SMOD class code.

Figure 16. Screen capture of a MS Office Excel session with an example of GHS-SMOD statistics by region

| | A | B | C | D | E | F | G | H |
|---|--------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------|
| 1 | Region_label | L2_class_10_pop_count | L2_class_11_pop_count | L2_class_12_pop_count | L2_class_13_pop_count | L2_class_21_pop_count | L2_class_22_pop_count | L2_class_23_pop_ |
| 2 | 3 | 0 | 84865.57207 | 424810.667 | 298744.4918 | 180203.8431 | 89337.49265 | 4026 |
| 3 | 14 | 0 | 94036.58292 | 545256.1956 | 728789.8971 | 309583.8826 | 230469.7552 | 3485 |
| 4 | 24 | 0 | 690226.0424 | 3500291.402 | 2325814.735 | 1395197.853 | 431035.0007 | 2656 |
| 5 | 27 | 0 | 28108.40367 | 231611.6033 | 177030.4639 | 71251.35648 | 56785.91312 | 2563 |

The filename is DUG_O{X}_L2_L1_stats_regions.xls (with X from 1 to 7).

4.2.2.3 Statistics by spatial entity

DUG computes basic statistics for each entity (available entities are listed in Table 17). The statics computed are:

1. Entity enclosed area in km²;
2. Entity enclosed population count;
3. Entity enclosed built-up area in km² (only when built-up area grid is provided by the user).

These values are saved in the attributes table of each entity shapefile.

Figure 17. Screen capture of a QGIS session with an example of spatial entity statistics

| | ID_UC | Area_km2 | Pop_count | Builtup_km2 |
|----|-------|----------|---------------|-------------|
| 1 | 7 | 18 | 58776.895050 | 7.395387 |
| 2 | 2 | 13 | 63921.917725 | 5.159350 |
| 3 | 1 | 13 | 54107.244202 | 2.862250 |
| 4 | 4 | 35 | 144246.621674 | 8.977819 |
| 5 | 3 | 29 | 147927.440063 | 10.950325 |
| 6 | 14 | 22 | 142461.287720 | 9.845706 |
| 7 | 13 | 12 | 78188.381165 | 3.496750 |
| 8 | 16 | 12 | 88048.113525 | 4.831875 |
| 9 | 15 | 14 | 81811.688126 | 2.164825 |
| 10 | 10 | 64 | 428807.582523 | 24.946881 |
| 11 | 9 | 42 | 184213.866428 | 12.078563 |
| 12 | 12 | 42 | 232087.884926 | 11.897681 |

5 Conclusion

The DUG Tool 3.0 adds to the family of GHSL open and free tools to enact the “open input, open method, open output” paradigm of the Global Human Settlement Layer framework. With the DUG Tool presented in this report the user can produce settlement classification grids and related statistics for specific areas of interest and input data. This capability supports the endeavours of the European Commission and the partner Organisations of the voluntary commitment to develop a harmonised global definition of cities and settlements launched at the Habitat III conference in 2016. The tool specifically supports the capacity enhancement activities currently carried out jointly by the European Commission Directorate General for Regional and Urban Policy, the Directorate General Joint Research Centre and the United Nations Human Settlements Programme to assess the feasibility of applying a global definition of cities/urban areas in support of global monitoring of SDGs and the New Urban Agenda urban targets towards the 51st Session of the United Nations Statistical Commission.

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