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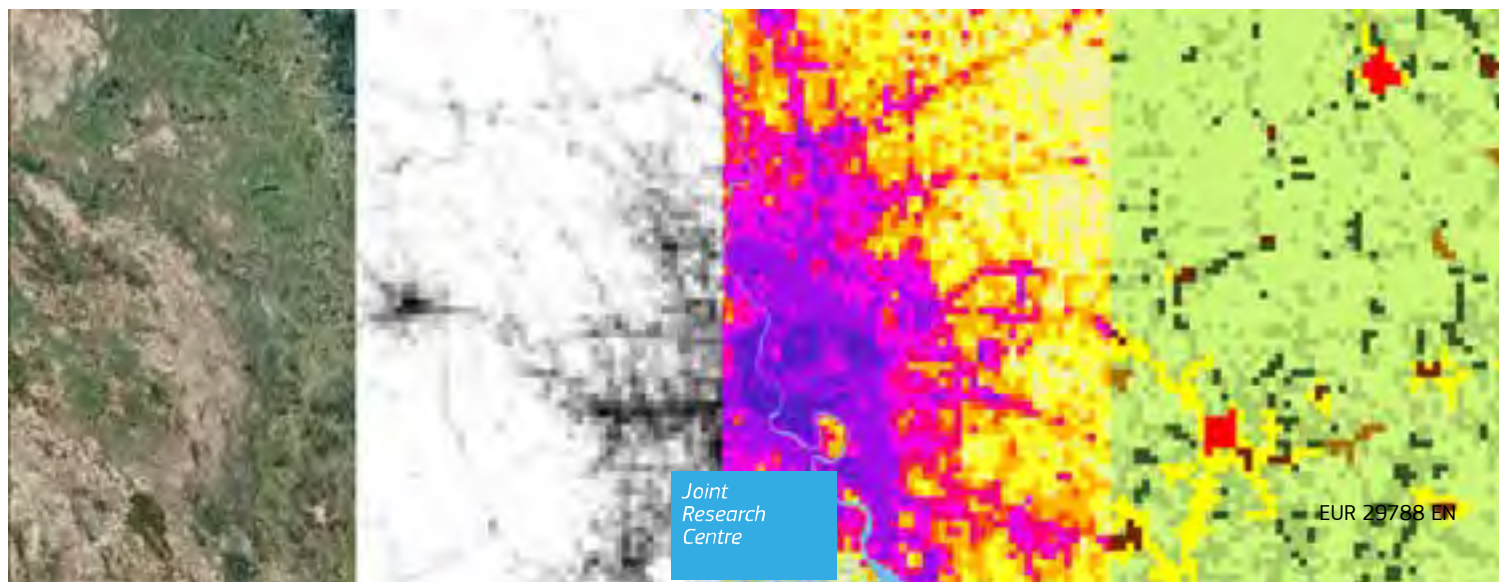
GHSL Data Package 2019

Public release
GHS P2019

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2019

Contents

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Abstract

The Global Human Settlement Layer (GHSL) produces new global spatial information, evidence-based analytics and knowledge describing the human presence on the planet Earth. The GHSL operates in a fully open and free data and methods access policy, building the knowledge supporting the definition, the public discussion and the implementation of European policies and the international frameworks such as the 2030 Development Agenda and the related thematic agreements. The GHSL supports the GEO Human Planet Initiative (HPI) that is committed to developing a new generation of measurements and information products providing new scientific evidence and a comprehensive understanding of the human presence on the planet and that can support global policy processes with agreed, actionable and goal-driven metrics. The Human Planet Initiative relies on a core set of partners committed in coordinating the production of the global settlement spatial baseline data. One of the core partners is the European Commission, Directorate General Joint Research Centre, Global Human Settlement Layer project. The Global Human Settlement Layer project produces global spatial information, evidence-based analytics, and knowledge describing the human presence on the planet.

This document describes the public release of the GHSL Data Package 2019 (GHS P2019). The release provides improved built-up area and population products as well as a new settlement model and functional urban areas

1 Introduction

1.1 Overview

The Global Human Settlement Layer (GHSL) project produces global spatial information, evidence-based analytics, and knowledge describing the human presence in the planet. The GHSL relies on the design and implementation of new spatial data mining technologies that allow automatic processing, data analytics and knowledge extraction from large amounts of heterogeneous data including global, fine-scale satellite image data streams, census data, and crowd sourced or volunteered geographic information sources.

This document accompanies the public release of the GHSL Data Package 2019 (GHS P2019) and describes the contents.

— Each product is named according to the following convention:

GHS_<name>_<temporalCoverage>_<spatialExtent>_<releaseId>

For example, a product name "GHS_BUILT_LDSMT_GLOBE_R2018A" indicates the GHSL Built-up area layer (GHS-BUILT) with multi-temporal coverage and a global spatial extent release R2019A.

— Each dataset is named according to the following convention:

GHS_<name>_<epochCode>_<extent>_<releaseId>_<EPSG>_<resolution>_<version>.<ext>

A dataset unique identifier like "GHS_POP_E2000_GLOBE_R2019A_54009_250_V1_0.tif" indicates the GHSL Population layer (GHS-POP) of the epoch 2000 with global extent, release R2019A in World Mollweide projection at 250 m resolution v1.0 in GeoTiff format.

The GHSL Data Package 2019 contains the following products:

— GHS Built-up area grid (GHS-BUILT), derived from Sentinel-1 (2016), R2018A [GHS_BUILT_S1NODSM_GLOBE_R2018A]. This product was distributed as part of the Community pre-Release of the GHSL Data Package 2018 (GHS CR2018) (Florczyk *et al.* 2018);

— GHS Built-up area grid (GHS-BUILT), derived from Landsat, multi-temporal (1975-1990-2000-2014), R2018A [GHS_BUILT_LDSMT_GLOBE_R2018A];

— GHS population grid (GHS-POP), derived from GPW4.1, multi-temporal (1975-1990-2000-2015), R2019A [GHS_POP_MT_GLOBE_R2019A]. This product was distributed as part of the Community pre-Release of the GHSL Data Package 2018 (GHS CR2018) (Florczyk *et al.* 2018); however, an updated version of the datasets is available (v2.0);

— GHS Settlement Model grid (GHS-SMOD), derived from GHS-POP and GHS-BUILT, multi-temporal (1975-1990-2000-2015), R2019A [GHS_SMOD_POPMT_GLOBE_R2019A].

1.2 Rationale

Open data and free access are core of principles GHSL (Melchiorri et al., 2019). They are in-line with the Directive on the re-use of public sector information (Directive 2003/98/EC[1]). The free and open access policy facilitates the information sharing and collective knowledge building, thus contributing to a democratisation of the information production.

The GHSL Data Package 2019 contains the new GHSL data produced at the European Commission Directorate General Joint Research Centre in the Directorate for Space, Security and Migration in the Disaster Risk Management Unit (E.1) in the period 2017 – 2019.

1.3 History and Versioning

In 2016 the first GHSL Data Package was released (GHS P2016). It consisted in several multi-temporal and multi-resolution products, including built-up area grids (GHS-BUILT), population grids (GHS-POP), settlement model (GHS-SMOD) and selected quality grids (data mask and confidence grids for GHS-BUILT).

The GHS-BUILT product is the result of a large scale experiment conducted in 2014/1025 aimed at extracting information on built-up areas from Landsat (Pesaresi et al., 2016a), producing the first multi-temporal explicit description of the evolution of built-up presence in the past 40 years. The main product is the

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[1] http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32003L0098

GHS_BUILT_LDSMT_GLOBE_R2015B[2] (Pesaresi et al., 2015), and two quality grids accompany it: (1) a built-up confidence layer (GHS_BUILTt_LDSMTCNFD_GLOBE_R2015B[3]) and (2) data mask layer (GHS_BUILTt_LDSMTDM_GLOBE_R2015B[4]).

The population grids (GHS_POP_GPW41MT_GLOBE_R2016A[5]) were produced in collaboration with Columbia University, Center for International Earth Science Information Network (CIESIN) in 2015, and the GHS-SMOD grids (GHS_SMOD_POP_GLOBE_R2016A[6]) present an implementation of the REGIO degree of urbanization model using as input the population grid cells.

The products from the GHS R2016 are available at GHSL collection in JRC Open Data Repository[7].

In 2017, a revised image processing workflow was implemented in the JRC Earth Observation Data and Processing Platform (JEODPP), and applied the Landsat multi-temporal imagery collection. As a result, an updated version of the multi-temporal built-up area and population grids has been produced, GHS_BUILT_LDSMT_GLOBE_R2018A and GHS_POP_GPW41MT_GLOBE_R2018A respectively. These early version of the products were distributed only for testing purposes as "preliminary" within the Community pre-Release of the GHSL Data Package 2018 (GHS CR2018) (Florczyk et al., 2018a), together with the GHS_BUILT_S1NODSM_GLOBE_R2018A.

Current data release contains the most updated products and datasets, therefore all previous releases and versions shall be treated as obsolete data.

1.4 Main Characteristics

In order to facilitate the data analytics, as it was done in the GHS P2016, the release includes a set of multi-resolution products produced by aggregation of the main products. Additionally, the density grids are produced in an equal-area projection in grids of 250 m and 1 km spatial resolution. For example, the multi-temporal population grids were produced in grids of 250 m spatial resolution, later aggregated to 1 km^2.

The main differences between the products in GHS P2016 and the current products (GHS P2019) are:

— Improved workflow for built-up area extraction from satellite image, for example, refined learning datasets (e.g., GHS_BUILT_S1NODSM_GLOBE_R2018A_V1_0), production at 30 m spatial resolution;

— Improved approach for production of population grids;

— Technical specification of the grids (i.e., the grid origin);

— Encoding of NoData values (e.g., projection domain, NoData within the data domain).

— Production of population grids in WGS 1984 coordinate system through a thorough volume-preserving warping procedure.

— Improved formulation of the settlement model GHS-SMOD with two hierarchical levels.

The subsections of the Section 2 introduce briefly each product (including more details on differences with the corresponding past version). Dedicated reports are under preparation.

1.5 Terms of Use

The data in this data package are provided free-of-charge © European Union, 2019. Reuse is authorised, provided the source is acknowledged. The reuse policy of the European Commission is implemented by a Decision of 12 December 2011 (2011/833/EU). For any inquiry related to the use of these data please contact the GHSL data producer team at the electronic mail address:

JRC-GHSL-DATA@ec.europa.eu

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[2] http://data.europa.eu/89h/jrc-ghsl-GHS_built_ldsmt_globe_r2015b
[3] http://data.europa.eu/89h/jrc-ghsl-GHS_built_ldsmtcnfd_globe_r2015b
[4] http://data.europa.eu/89h/jrc-ghsl-GHS_built_ldsmtdm_globe_r2015b
[5] http://data.europa.eu/89h/jrc-ghsl-GHS_pop_gpw4_globe_r2015a
[6] http://data.europa.eu/89h/jrc-ghsl-GHS_smod_pop_globe_r2016a
[7] http://data.jrc.ec.europa.eu/collection/ghsl

Disclaimer: The JRC data are provided "as is" and "as available" in conformity with the JRC Data Policy[8] and the Commission Decision on reuse of Commission documents (2011/833/EU). Although the JRC guarantees its best effort in assuring quality when publishing these data, it provides them without any warranty of any kind, either express or implied, including, but not limited to, any implied warranty against infringement of third parties' property rights, or merchantability, integration, satisfactory quality and fitness for a particular purpose. The JRC has no obligation to provide technical support or remedies for the data. The JRC does not represent or warrant that the data will be error free or uninterrupted, or that all non-conformities can or will be corrected, or that any data are accurate or complete, or that they are of a satisfactory technical or scientific quality. The JRC or as the case may be the European Commission shall not be held liable for any direct or indirect, incidental, consequential or other damages, including but not limited to the loss of data, loss of profits, or any other financial loss arising from the use of the JRC data, or inability to use them, even if the JRC is notified of the possibility of such damages.

> **Prior to cite this report, please access the updated version available at:**
> http://ghsl.jrc.ec.europa.eu/documents/GHSL_Data_Package_2019.pdf

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[1] JRC Data Policy https://doi.org/10.2788/607378

2 Products

2.1 GHS built-up area grid, derived from Sentinel-1 (2016), R2018A [GHS_BUILT_S1NODSM_GLOBE_R2018A]

The Sentinel-1 product is a layer grid that contains a built-up area classification derived from Sentinel-1 backscatter images. This product increases the spatial coverage of the product produced in 2016, referred to as GHS_BUILT_S12016NODSM_GLOBE_R2016A. The same product has been distributed within the Community pre-Release of the GHSL Data Package 2018 (GHS CR2018).

The information extraction of Sentinel-1A data at global scale is described in a scientific publication (Corbane et al., 2018a). The main workflow builds on a new artificial intelligence approach for the satellite data classification process named "Symbolic Machine Learning" (SML) (Pesaresi et al., 2016a). The SML classifier automatically generates inferential rules linking the image data to available high-abstraction semantic layers used as training sets.

The SML workflow was adapted to exploit the key features of the Sentinel-1 Ground Range Detected (GRD) data which are: i) the spatial resolution of 20m with a pixel spacing of 10m and ii) the availability of dual polarisation acquisitions (VV and VH) widely used for monitoring urban areas since different polarizations have different sensitivities and different backscattering coefficients for the same target.

The learning data at the global level consisted of the union of the built-up obtained from the GHSL-Landsat for 2014 and the Global Land Cover map at 30 m resolution (GLC30). The latter has been also derived from Landsat imagery through operational visual analysis techniques (Chen *et al.*, 2015).

The massive processing of more than 7,000 Sentinel-1 scenes (Figure 1) was enabled by JEODPP platform developed in the framework of the JRC Big Data Pilot Project. The platform is set-up to answer the emerging needs of the JRC Knowledge Production units following the new challenges posed by Earth Observation entering the big data era.

Figure 1 Mosaic of the S1 scenes processed within the SML for extracting built-up areas

2.1.1 Input Data

The input imagery collection consists of Sentinel-1A (S1A) and Sentinel-1B (S1B) images:

— 5,026 S1A images from December 2015 to October 2016;

— 1,695 S1A and 329 S1B images from November 2016 to December 2017.

2.1.2 Technical Details

Author: Christina Corbane, Panagiotis Politis, Vasileios Syrris, Martino Pesaresi; Joint Research Centre (JRC) European Commission

Product name: GHS_BUILT_S1NODSM_GLOBE_R2018A

Spatial extent: Global

Temporal extent: 2016

Coordinate System: Spherical Mercator (EPSG:3857)

Resolution available: 20 m

Encoding*: Built-up area classification map (integer) [0,1];

Data organisation (*): VRT file (with TIFF tiles); pyramids; SHP file of the tile schema. **ArcGIS users of the 30 m product: *ESRI.vrt. file**

The grid is provided as a VRT file (with GeoTIFF tiles), and with pyramids. Table 1 below outlines the technical characteristics of the datasets pre-Released in this data package.

Table 1. Technical details of the datasets in GHS_BUILT_S1NODSM_GLOBE_R2018A

GHS_BUILT_S1NODSM_GLOBE_R2018A			
ID	**Description**	**Resolution (projection)**	**Size**
GHS_BUILT_S1NODSM _GLOBE_R2018A _3857_20_V1_0.vrt	Classification map depicting built-up presence. 0 = no built-up or no data 1 = built-up are **ArcGIS users: *ESRI.vrt.file**	20 m (Pseudo Mercator)	8.6 GB

2.1.3 How to cite

Dataset:

Corbane, Christina; Politis, Panagiotis; Syrris, Vasileios; Pesaresi, Martino (2018): GHS built-up grid, derived from Sentinel-1 (2016), R2018A. European Commission, Joint Research Centre (JRC) doi:10.2905/jrc-ghsl-10008 PID: http://data.europa.eu/89h/jrc-ghsl-10008

Concept & Methodology:

Corbane, Christina; Pesaresi, Martino; Politis, Panagiotis; Syrris, Vasileios; Florczyk, Aneta J.; Soille, Pierre; Maffenini, Luca; Burger, Armin; Vasilev, Veselin; Rodriguez, Dario; Sabo, Filip; Dijkstra, Lewis; Kemper, Thomas (2017): Big earth data analytics on Sentinel-1 and Landsat imagery in support to global human settlements mapping, Big Earth Data, 1:1-2, 118-144, DOI: 10.1080/20964471.2017.1397899

2.2 GHS built-up area grid (GHS-BUILT), derived from Landsat, multi-temporal (1975-1990-2000-2014), R2018A [GHS_BUILT_LDSMT_GLOBE_R2018A]

The Landsat product contains a set of multi-temporal and multi-resolution grids. The main product is the multi-temporal classification layer on built-up presence derived from the Global Land Survey (GLS) Landsat[9] image collections (GLS1975, GLS1990, GLS2000, and ad-hoc Landsat 8 collection 2013/2014). This data release contains version 2.0 of the product which is an updated version of the one distributed within the Community pre-Release of the GHSL Data Package 2018 (GHS CR2018).

2.2.1 Improvements comparing to the previous version

The satellite-derived information extraction tasks included in the GHSL production workflow used to produce the products GHS_BUILT_LDSMT_GLOBE_R2015B and GHS_BUILT_LDSMT_GLOBE_R2018A, builds on the Symbolic Machine learning (SML) method that was designed for remote sensing big data analytics (Pesaresi et al., 2016b). For the purpose of the GHS_BUILT_LDSMT_GLOBE_R2018A, a revised image processing workflow was implemented in the JRC Earth Observation Data and Processing Platform (JEODPP).

Comparing to the previous publicly released version (R2015B), these datasets include a number of improvements, as shown through visual comparison in Figure 2. Such improvement are:

— Improved spatial coverage (additional Landsat 8 scenes)

— Improved spatial resolution (30 m)

— Improved methods (e.g., improved learning data set), which resulted in:

   o   Reduction in omission error (i.e. more built-up areas were detected)

   o   Reduction in commission error (i.e. less detection of false built-up areas)

Corbane et al., (2019) explains in detail the rationale, the workflow deployed to generate the layer, mainly the usage of the GHSL Sentinel-1 data set (GHS_BUILT_S1NODSM_GLOBE_R2018A) as a learning dataset, and the multi-temporal validation of the layer.

2.2.2 Input Data

The new product GHS_BUILT_LDSMT_GLOBE_R2018A (version 2.0) is based on 33,202 images (Florczyk et al., 2018b) organized in four Landsat data collections centred at 1975, 1990, 2000 and 2014 that were processed with the SML classifier as follows:

— 7,597 scenes acquired by the Multispectral Scanner (collection 1975);

— 7,375 scenes acquired by the Landsat 4-5 Thematic Mapper (TM) (collection 1990);

— 8,788 scenes acquired by the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (collection 2000) and;

— 9,442 scenes acquired by Landsat 8 (collection 2014).

2.2.3 Technical Details

Author: Christina Corbane, Aneta .J. Florczyk, Martino Pesaresi, Panagiotis Politis, Vasileius Syrris; Joint Research Centre (JRC) European Commission

Product name: GHS_BUILT_LDSMT_GLOBE_R2018A

Spatial extent: Global

Temporal extent: 1975-1990-2000-2014

Coordinate Systems*: Spherical Mercator (EPSG:3857), World Mollweide (EPSG:54009)

Resolutions available*: 30 m, 250 m, 1 km

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[9] http://glcf.umd.edu/data/gls/

Encoding*: Multi-temporal built-up area classification map (integer): [1,6], NoData: 0; Built-up density grid (float32): [0-100], NoData [-200]

Data organisation (*): VRT file (with GeoTIFF tiles) or GeoTIFF files; as single global layers, with pyramids and SHP file of tile schema, or tiled; **ArcGIS users of the 30 m product: *ESRI.vrt.file**.

Table 2 outlines the technical characteristics of the datasets released in this data package.

(*) product dependent, see Table 2. Disclaimer: the re-projection of the World Mollweide version of the GHS_BUILT_LDSMT_GLOBE_R2018A to coordinate systems requires specific technical knowledge. No responsibility is taken for workflows developed independently by users.
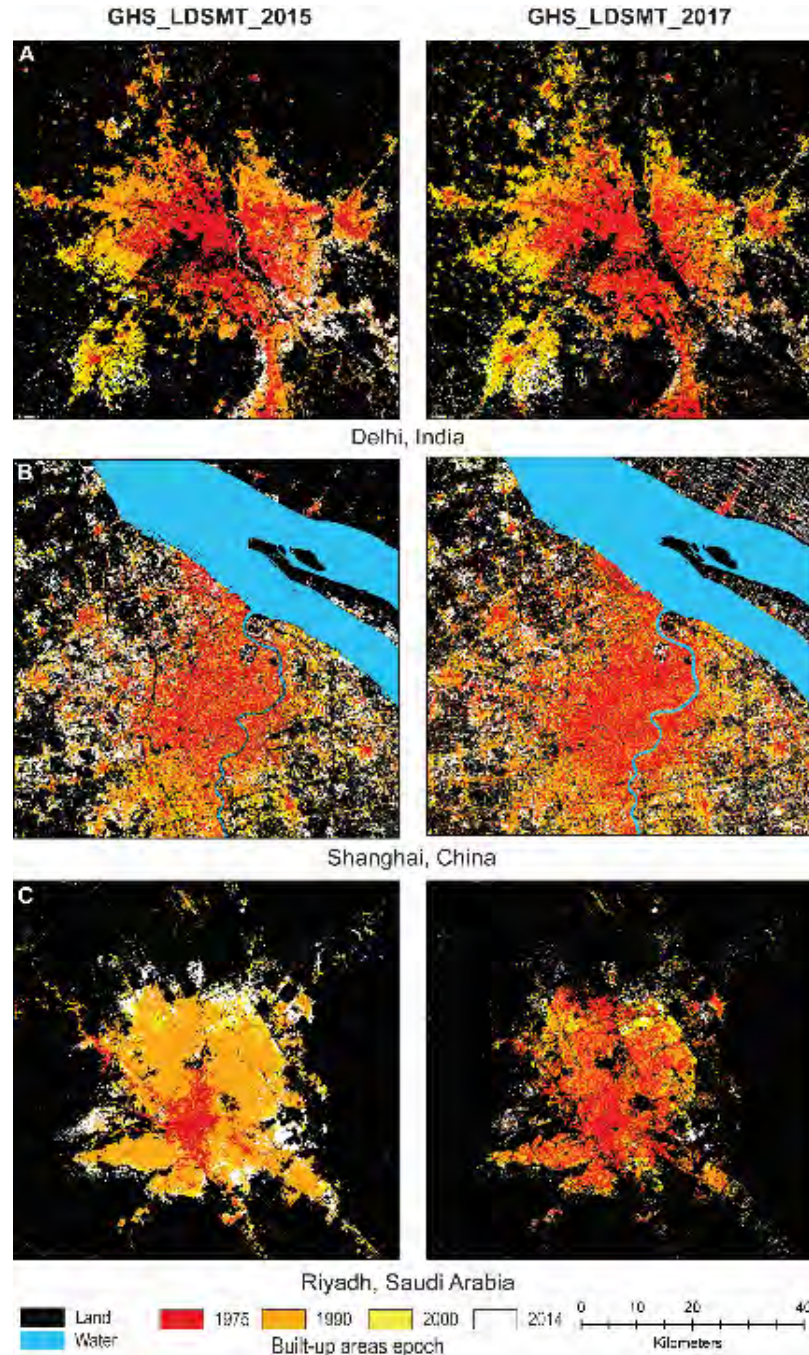
Figure 2 Comparison between GHS_BUILT_LDSMT_GLOBE_R2015B (left panel – GHS_LDSMT_2015) and GHS_BUILT_LDSMT_GLOBE_R2018A, version 2.0 (right panel – GHS_LDSMT_2017). In Corbane et al. (2019)

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Table 2. Technical details of the datasets in GHS_BUILT_ LDSMT_GLOBE_R2018A

ID	Description	Resolution (projection)	Size
GHS_BUILT_LDSMT_GLOBE_R2018A			
GHS_BUILT_LDSMT _GLOBE_R2018A _3857_30_V2_0	Multi-temporal classification of built-up presence. 0 = no data 1 = water surface 2 = land no built-up in any epoch 3 = built-up from 2000 to 2014 epochs 4 = built-up from 1990 to 2000 epochs 5 = built-up from 1975 to 1990 epochs 6 = built-up up to 1975 epoch **ArcGIS users: *ESRI.vrt.file**	30 m (Pseudo Mercator)	4.3 GB
GHS_BUILT_LDS2014 _GLOBE_R2018A _54009_250_V2_0	Built-up area density for epoch 2014, aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	250 m (World Mollweide)	398 MB
GHS_BUILT_LDS2000 _GLOBE_R2018A _54009_250_V2_0	Built-up area density for epoch 2000, aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	250 m (World Mollweide)	353 MB
GHS_BUILT_LDS1990 _GLOBE_R2018A _54009_250_V2_0	Built-up area density for epoch 1990, aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	250 m (World Mollweide)	316 MB
GHS_BUILT_LDS1975 _GLOBE_R2018A _54009_250_V2_0	Built-up area density for epoch 1975, aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	250 m (World Mollweide)	274 MB
GHS_BUILT_LDS2014 _GLOBE_R2018A _54009_1K_V2_0	Built-up area density for epoch 2014, aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	1 km (World Mollweide)	86 MB
GHS_BUILT_LDS2000 _GLOBE_R2018A _54009_1K_V2_0	Built-up area density for epoch 2000, aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	1 km (World Mollweide)	76 MB
GHS_BUILT_LDS1990 _GLOBE_R2018A _54009_1K_V2_0	Built-up area density for epoch 1990. Aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	1 km (World Mollweide)	68 MB
GHS_BUILT_LDS1975 _GLOBE_R2018A _54009_1K_V2_0	Built-up area density for epoch 1975. Aggregated from 30 m. Values are expressed as decimals (Float) from 0 to 100 NoData [-200]: -200 – out of projection domain or NoData	1 km (World Mollweide)	58 MB

2.2.4 Summary statistics

Table 3 Summary statistics of total global built-up area in square kilometre as obtained from the 1-km World Mollweide grid (Corbane et al., 2019)

	1975	1990	2000	2014
Built-up area (km^2)	379,552	523,333	655,742	789,385

2.2.5 How to cite

Dataset:

Corbane, Christina; Florczyk, Aneta; Pesaresi, Martino; Politis, Panagiotis; Syrris, Vasileios (2018): GHS built-up grid, derived from Landsat, multitemporal (1975-1990-2000-2014), R2018A. European Commission, Joint Research Centre (JRC) doi:10.2905/jrc-ghsl-10007 PID: http://data.europa.eu/89h/jrc-ghsl-10007

Concept & Methodology:

Corbane, Christina., Pesaresi, Martino., Kemper, Thomas., Politis, Panagiotis., Florczyk, Aneta J., Syrris, Vasileios, Melchiorri, Michele, Sabo, Filip, and Soille, Pierre (2019). Automated global delineation of human settlements from 40 years of Landsat satellite data archives. Big Earth Data 3, 140–169. DOI:10.1080/20964471.2019.1625528

2.3 GHS population grid (GHS-POP), derived from GPW4.10, multi-temporal (1975-1990-2000-2015), R2019A [GHS_POP_MT_GLOBE_R2019A]

This spatial raster product depicts the distribution and density of population (Figure 3), expressed as the number of people per cell. Residential population estimates for target years 1975, 1990, 2000 and 2015 provided by CIESIN Gridded Population of the World, version 4.10 (GPWv4.10) at polygon level, were disaggregated from census or administrative units to grid cells, informed by the distribution and density of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer per corresponding epoch. The disaggregation methodology is described in a conference scientific paper (Freire et al., 2016)). This an updated version of the product (GHS_POP_GPW41MT_GLOBE_R2018A) distributed within the Community pre-Release of the GHSL Data Package 2018 (GHS CR2018).
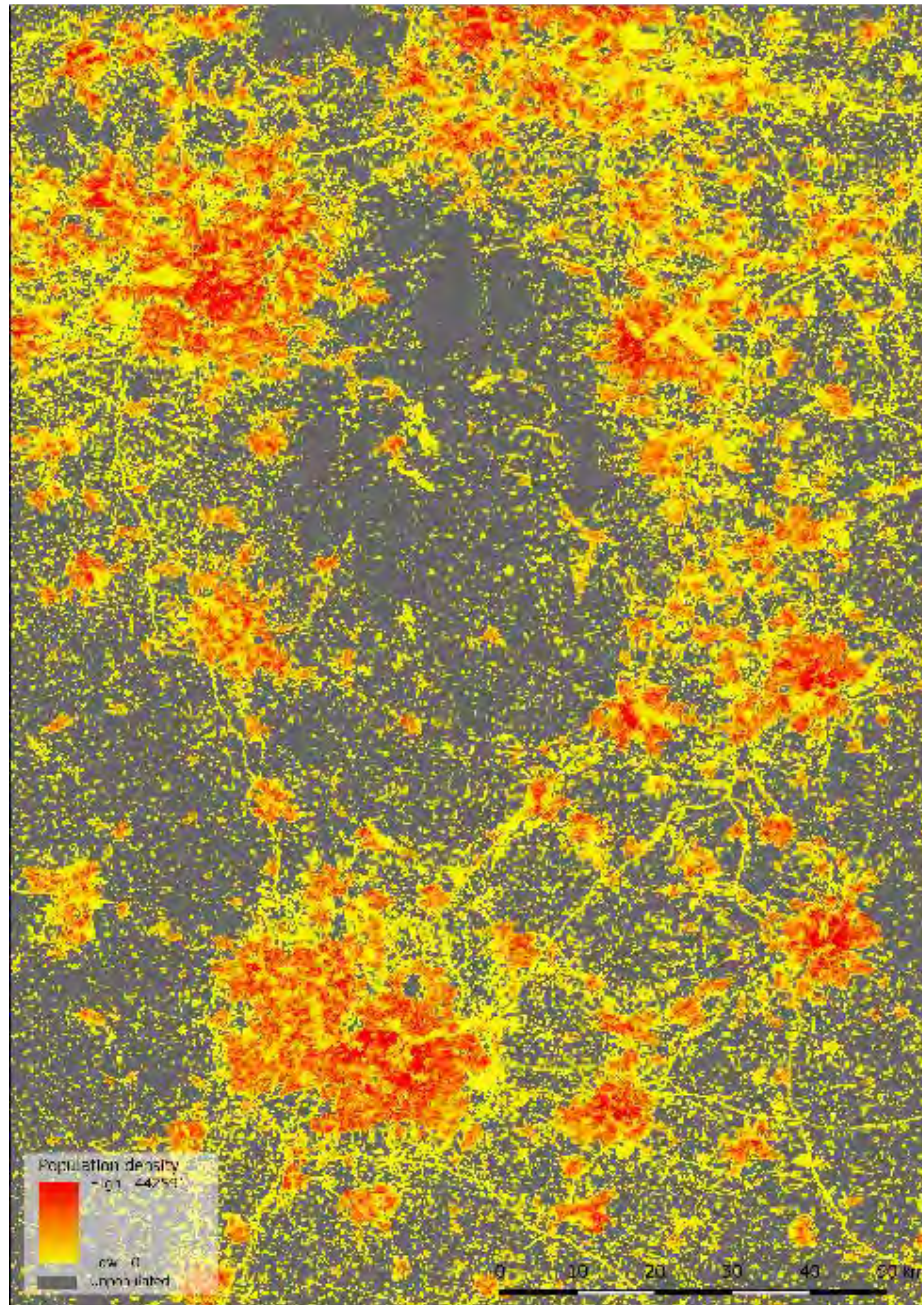

Figure 3 GHS Population grid (GHS-POP) GHS_POP_E2015_GLOB_R2019A_54009_250_V1_0 displayed in West Midlands (United Kingdom).

2.3.1   Improvements comparing to the previous version

The new version of the GHSL population distribution grids aimed at incorporating improvements originating from input datasets, namely population estimates and built-up presence. While the disaggregation relied essentially on the same clear and simple approach, there were significant differences to the input data that had a positive effect on the final quality and accuracy of population grids. Here, we describe the main differences between the currently released products (GHS_POP_MT_GLOBE_R2019A) and the previous one (GHS_POP_GPW41_GLOBE_R2015A), for more information on these improvements, see the related scientific publication (Freire et al., 2018).

For the new GHS-POP (GHS_POP_MT_GLOBE_R2019A), the new Landsat based GHS-BUILT (GHS_BUILT_LDSMT_GLOBE_R2018A, version 2.0) was used as target for disaggregation of population estimates. Cells declared as "NoData" in built-up layers were treated as zero for population disaggregation.

The base source of population estimates (both counts and geometries) for the four epochs mapped was the Gridded Population of the World, version 4.10 (GPWv4.10), from CIESIN/SEDAC. Respect to the previous release of GHSL Data Package 2016 (GHS P2016), this release used GPW source data that incorporated boundary or population updates for 67 countries.

Due to the previous GHSL population grids being produced in last quarter of 2015, before the final GPWv4 data set was fully assembled, more changes were included in population sources in the current release than those incorporated in the GPW data between GPWv4 and the current GPWv4.10. For detailed information on what has changed in GPWv4.10, refer to:

https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/whatsnewrev10

GHS-POP product is produced in Mollweide at 250 m, and then aggregated at 1 km. These two datasets are then warped to WGS 1984 coordinate system, at 9 arcsec and 30 arcsec resolution respectively, by applying a thorough volume-preserving procedure (i.e. oversampling at 10-times higher resolution; transformation of raster to points, using cell centroids; vector warping to WGS 1984; and rasterization in the final grid by adding point values per pixel).

2.3.1.1   *Harmonisation of Coastlines*

Seashore and waterfront can be especially intense and dynamic zones, contributing to making census or administrative geometries outdated and inaccurate. Inconsistencies between census data and GHSL along coastlines (including inland water bodies) were detected and reconciled accordingly. The high-resolution GHSL layer on built-up areas for 2014 (from R2015B) was used to detect significant human presence (i.e. built-up areas presence) beyond censuses' coastlines and these lines were reconciled accordingly. This harmonization was carried out in the following countries:

Albania	France	Singapore
Austria	Guinea-Bissau	Sweden
Azerbaijan	Iceland	Tunisia
Bulgaria	Japan	Ukraine
Bahrain	Republic of Korea	USA
Switzerland	Malaysia	Venezuela
Germany	Netherlands	Viet Nam
Denmark	Norway	
United Arab Emirates	Romania	
Finland	Russia	

2.3.1.2 Revision of Unpopulated Areas

Units deemed as "uninhabited" in the census data were critically assessed for presence of residential population, based on ancillary data and high-resolution imagery. Inconsistencies between census data and contradicting evidence were detected and reconciled accordingly. An automated method was devised to split and merge these polygons, based on geographical proximity, with those ones adjacent and containing population. This procedure was implemented while minimizing changes to source geometry, preserving the regional distribution of population, and the overall counts. This procedure was carried out in the following countries:

Afghanistan	Egypt	Malawi
Armenia	Georgia	Nepal
Democratic Republic of the Congo	Guyana	Rwanda
Colombia	Iraq	Thailand
Cyprus	Lebanon	Ukraine
	Mali	

2.3.2 Input Data

The new product GHS_BUILT_LDSMT_GLOBE_R2018A (version 2.0) was used as target for disaggregation of population estimates. The base source of population estimates for the four epochs was the Gridded Population of the World, version 4.10 (GPWv4.10), from CIESIN/SEDAC, with some modifications as described above.

2.3.3 Technical Details

Author: Sergio Freire, Marcello Schiavina, Joint Research Centre (JRC) European Commission; *Kytt MacManus* Columbia University, Center for International Earth Science Information Network – CIESIN.

Product name: GHS_POP_MT_GLOBE_R2019A

Spatial extent: Global

Temporal extent: 1975-1990-2000-2015

Coordinate Systems: World Mollweide (EPSG: 54009) and WGS 1984 (EPSG: 4326)

Resolutions available: 250 m, 1 km, 9 arcsec, 30 arcsec

Encoding: Population data float32 [0, ∞); NoData: -200

Data organisation: The grids are provided as GeoTIFF file as single global layer with pyramids or tiled.

Table 4 outlines the technical characteristics of the datasets released in this data package.

Table 4. Technical details of the datasets in GHS_POP_MT_GLOBE_R2019A

GHS_POP_MT_GLOBE_R2019A			
ID	**Description**	**Resolution (Projection/Coordinate system)**	**Size**
GHS_POP_E2015_ GLOBE_R2019A _54009_250_V1_0	Population density for epoch 2015 Values are expressed as decimals (Float) from 0 to 442591 NoData [-200]	250 m (World Mollweide)	515 MB
GHS_POP_E2000_ GLOBE_R2019A _54009_250_V1_0	Population density for epoch 2000 Values are expressed as decimals (Float) from 0 to 303161 NoData [-200]	250 m (World Mollweide)	476 MB
GHS_POP_E1990_ GLOBE_R2019A _54009_250_V1_0	Population density for epoch 1990 Values are expressed as decimals (Float) from 0 to 237913 NoData [-200]	250 m (World Mollweide)	451 MB

GHS_POP_MT_GLOBE_R2019A			
ID	**Description**	**Resolution (Projection/Coordinate system)**	**Size**
GHS_POP_E1975 _GLOBE_R2019A _54009_250_V1_0	Population density for epoch 1975 Values are expressed as decimals (Float) from 0 to 899329 NoData [-200]	250 m (World Mollweide)	427 MB
GHS_POP_E2015 _GLOBE_R2019A _54009_1K_V1_0	Population density for epoch 2015 Values are expressed as decimals (Float) from 0 to 442591 NoData [-200]	1 km (World Mollweide)	124 MB
GHS_POP_E2000 _GLOBE_R2019A _54009_1K_V1_0	Population density for epoch 2000 Values are expressed as decimals (Float) from 0 to 341997 NoData [-200]	1 km (World Mollweide)	121 MB
GHS_POP_E1990 _GLOBE_R2019A _54009_1K_V1_0	Population density for epoch 1990 Values are expressed as decimals (Float) from 0 to 1013921 NoData [-200]	1 km (World Mollweide)	120 MB
GHS_POP_E1975 _GLOBE_R2019A _54009_1K_V1_0	Population density for epoch 1975 Values are expressed as decimals (Float) from 0 to 3017848 NoData [-200]	1 km (World Mollweide)	122 MB
GHS_POP_E2015 _GLOBE_R2019A _4326_9SS_V1_0	Population count for epoch 2015 Values are expressed as decimals (Float) from 0 to 302832 NoData [-200]	9 arcsec (WGS84)	1.52 GB
GHS_POP_E2000 _GLOBE_R2019A _4326_9SS_V1_0	Population count for epoch 2000 Values are expressed as decimals (Float) from 0 to 209939 NoData [-200]	9 arcsec (WGS84)	1.50 GB
GHS_POP_E1990 _GLOBE_R2019A _4326_9SS_V1_0	Population count for epoch 1990 Values are expressed as decimals (Float) from 0 to 164755 NoData [-200]	9 arcsec (WGS84)	1.53 GB
GHS_POP_E1975 _GLOBE_R2019A _4326_9SS_V1_0	Population count for epoch 1975 Values are expressed as decimals (Float) from 0 to 611544 NoData [-200]	9 arcsec (WGS84)	1.58 GB
GHS_POP_E2015 _GLOBE_R2019A _4326_30SS_V1_0	Population count for epoch 2015 Values are expressed as decimals (Float) from 0 to 459435 NoData [-200]	30 arcsec (WGS84)	240 MB
GHS_POP_E2000 _GLOBE_R2019A _4326_30SS_V1_0	Population count for epoch 2000 Values are expressed as decimals (Float) from 0 to 303161 NoData [-200]	30 arcsec (WGS84)	237 MB
GHS_POP_E1990 _GLOBE_R2019A _4326_30SS_V1_0	Population count for epoch 1990 Values are expressed as decimals (Float) from 0 to 650409 NoData [-200]	30 arcsec (WGS84)	241 MB
GHS_POP_E1975 _GLOBE_R2019A _4326_30SS_V1_0	Population count for epoch 1975 Values are expressed as decimals (Float) from 0 to 2109200 NoData [-200]	30 arcsec (WGS84)	247 MB

2.3.4   Summary statistics

Table 5 Summary statistics of total population as obtained from the 1-km World Mollweide grid as obtained from GPW4.10 – total population adjusted to the UN WPP 2015 (United Nations, Department of Economic and Social Affairs, Population Division, 2015).

	1975	1990	2000	2015
Total Population	4,061,348,355	5,309,597,005	6,126,529,207	7,349,329,050

2.3.5 How to cite

Dataset:

Schiavina, Marcello; Freire, Sergio; MacManus, Kytt (2019): GHS population grid multitemporal (1975-1990-2000-2015), R2019A. European Commission, Joint Research Centre (JRC) [Dataset] doi:10.2905/0C6B9751-A71F-4062-830B-43C9F432370F PID: http://data.europa.eu/89h/0c6b9751-a71f-4062-830b-43c9f432370f

Concept & Methodology:

Freire, Sergio; MacManus, Kytt; Pesaresi, Martino; Doxsey-Whitfield, Erin; Mills, Jane (2016): Development of new open and free multi-temporal global population grids at 250 m resolution. Geospatial Data in a Changing World; Association of Geographic Information Laboratories in Europe (AGILE). AGILE 2016.

2.4 GHS Settlement Model layers (GHS-SMOD), derived from GHS-POP and GHS-BUILT, multi-temporal (1975-1990-2000-2015), R2019A [GHS_SMOD_POPMT_GLOBE_R2019A]

The GHS Settlement Model layers (GHS-SMOD) GHS_SMOD_POPMT_GLOBE_R2019A delineate and classify settlement typologies (Figure 4) via a logic of cell clusters population size, population and built-up area densities as a refinement of the 'degree of urbanisation' method as described by EUROSTAT[10]. The GHS-SMOD is derived from the GHS-POP (GHS_POP_MT_GLOBE_R2019A, version 1.0) and GHS-BUILT (GHS_BUILT_LDSMT_GLOBE_R2018A, version 2.0) released within this GHSL Data Package 2019 (GHS P2019).

The GHS Settlement Model layers (GHS-SMOD) GHS_SMOD_POPMT_GLOBE_R2019A is composed by two datasets: the GHS-SMOD raster grid and the urban centre entities vector. The first is a raster grid representing the settlement classification per grid cell and the second delineates the urban centre boundaries, with main attributes, in a vector file.
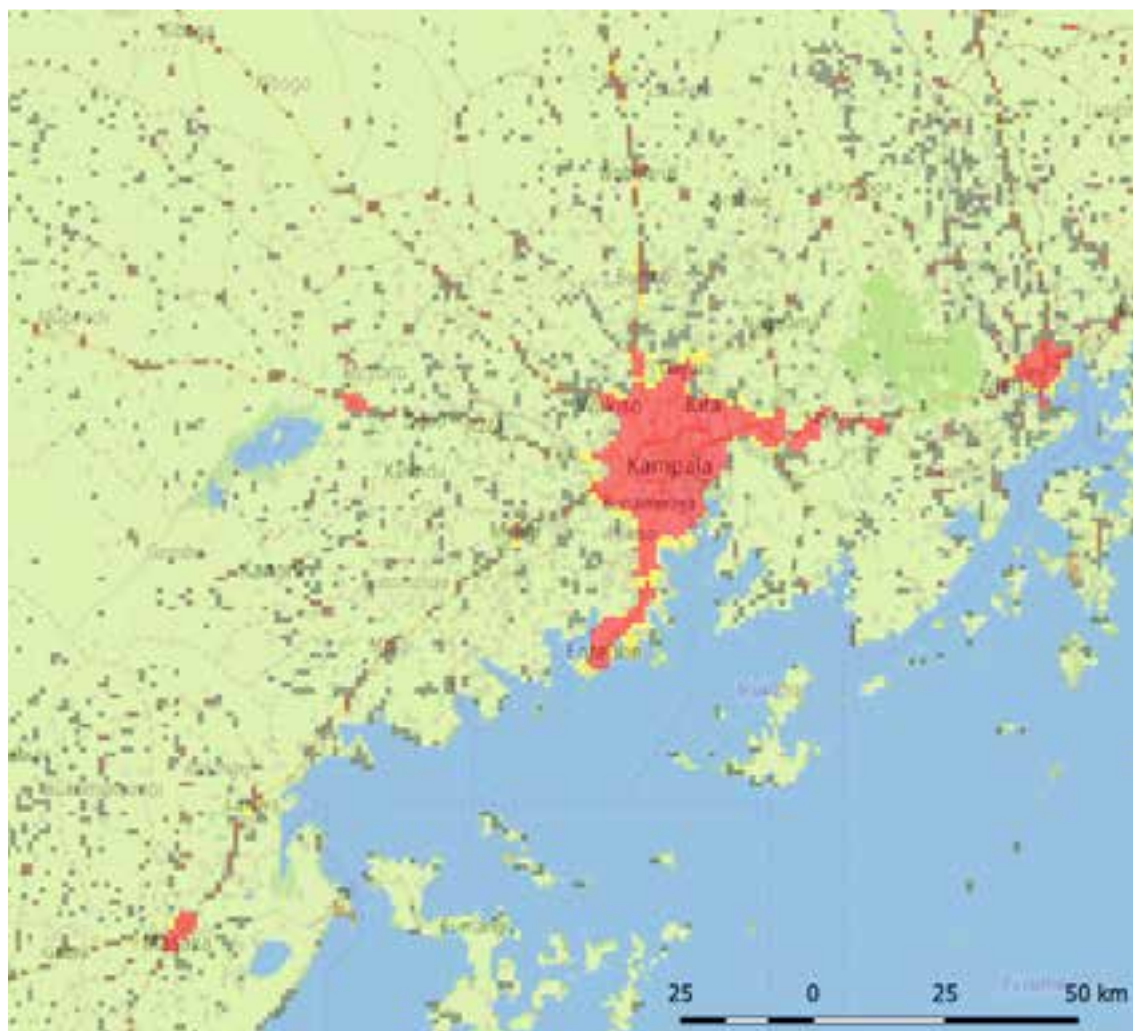

Figure 4 GHS Settlement Model grid (GHS-SMOD) GHS_SMOD_POP2015_GLOBE_R2019A_54009_1K_V2_0 displayed in the area of Kampala (Uganda) –Legend in Table 7. The boundaries and the names shown on this map do not imply official endorsement or acceptance by the European Union © OpenStreetMap

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[10] https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Degree_of_urbanisation

2.4.1 Improvements comparing to the previous version

The GHS-SMOD grid is an improvement of the GHS-SMOD R2016A introducing a more detailed classification of settlements in two levels, with a further development of the GHSL Settlement Model (GHSL SMOD). The GHS-SMOD is provided at the detailed level (Second Level - L2). First level, as a porting of the Degree of Urbanization adopted by EUROSTAT can be obtained aggregating L2 as shown in the first level (L1) description (see Table 6 p. 22).

2.4.2 GHSL Settlement model (GHSL SMOD)

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 Centre[11]. 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., 2018b; Melchiorri et al., 2019). The general GHSL SMOD operates in seven optional modalities (01 to 07), ordered from low to high number of model assumptions and necessary input data complexity (Maffenini et al., 2019). 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 specifications and quality control procedures. The GHS-SMOD grid is produced using the option 6 (06) which assumptions are listed below with a short description:

- **Basic criteria** (local population densities: 50, 300 and 1500; cluster 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.

    - o   Urban Centres use population density of 1500 inhabitants per km^2 and cluster population size of 50k inhabitants;

    - o   Urban Clusters use population density of 300 inhabitants per km^2 and cluster population size of 5k inhabitants;

    - o   Rural Clusters use population density of 300 inhabitants per km^2 and cluster population size of 500 inhabitants;

    - o   Low density Rural grid cells use population density of 50 inhabitants per km^2.

- **Permanent water surface excluded** - 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.

- **Density on permanent land** –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).

- **xbu_share 50%** - the Urban Centres are set by adding to the basic criteria (see point above) also those cells with at least 50% of built-up surface. 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 the basic criteria defines Urban Centres to be fully contained into Urban Clusters and the application of *xbu_share 50%* rule would break this hierarchy, this assumption extends the Urban Cluster domain to contain Urban Centres.

- **Generalization of HDC (smooth and gap filling)** –the clusters of the Urban Centres 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 km^2 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. Ideal typical case is the inclusion of large parks (less than 15 km^2) 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.

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[11] https://ghsl.jrc.ec.europa.eu/

- **_xbu_share 3%_** - 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 purpose of this assumption 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.

2.4.3 GHS-SMOD classification rules

With the described set of assumptions (GHSL SMOD 06), at the first hierarchical level (L1), 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 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 of permanent land or with a built-up surface share on permanent land greater than 0.5, and has at least 50,000 inhabitants in the cluster with smoothed boundaries and <15 km² holes filled;

- **_"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 of permanent land, a built-up surface share on permanent land greater than 0.03 and has at least 5,000 inhabitants in the cluster plus all contiguous (4-connectivity cluster) Urban Centres (see section 2.4.2 for details).

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 Rural grid cells 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 using the following set of codes (classes) and rules:

— **_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 (L2) 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 5).

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

- **_"Urban Centre" (also "Dense, Large Settlement" or "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 of permanent land or with a built-up surface share on permanent land greater than 0.5, and has at least 50,000 inhabitants in the cluster with smoothed boundaries and <15 km² holes filled;

- **_"Dense Urban Cluster" (also "Dense, Medium Cluster")_** – A Dense Urban Cluster 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 built-up surface share on permanent land greater than 0.5, and has at least 5,000 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 km^2 of permanent land, a built-up surface share on permanent land greater than 0.03, 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 km^2 of permanent land and has at least 500 and less than 5,000 inhabitants in the cluster.

The **"Suburban or peri-urban grid cells" (also Semi-dense grid cells)** are all the other cells that belong to an Urban Cluster (level 1 spatial entity) 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 km^2 (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 km^2 (grid cell).

The **"Water grid cells"** are all the cells with more than 0.5 share covered by permanent surface water not populated nor built.

The **settlement grid** at level 2 represents these definitions on a single layer grid. Each pixel is classified using the following set of codes (classes) and rules (Table 7):

— **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 the cell has 0.5 share covered by permanent surface water and is not populated nor built.

2.4.4 GHS_SMOD spatial entities naming

The highest tier spatial entities (Urban Centre) are named using an algorithm that automatically queries the GISCO and the full OpenStreetMap datasets with the following steps:

1 For each node of the dataset the reference name is selected among all the available naming tag with the following priority: *name_en*; *name_int*; *name* (if in Latin characters); *name_fr*; *name_es; name_it*; *name_de*; *name_wiki*; *name;*

2 The algorithm filters all nodes that overlaps the extent of the spatial entity in their 3 km buffer and selects among them the nodes with the highest priority using the following tag ordering (*key:value*): *place:city*; *place:town*; *place:village*; *place:hamlet*; *place:isolated_dwelling*; *place:farm*; *place:allotments*; *place:borough*; *place:suburb*; *place:quarter*; *place:neighbourhood*; *place:city_block*; *place:plot*; *place:locality*; *place:municipality*; *place:civil_parish*; *railway:station*; *addr:city*;

3 If a single node is selected the reference name is assigned to the spatial entity as main name; if multiple nodes are selected the function ranks the nodes by *population* tag values (descending order, absence of *population* tag equal 0); if no *population* tag is present, it ranks by sum of GHS-POP in the 5 km buffer around the point (descending order). The ordered list is saved and assigned to the spatial entity; the first name is selected as main name of the spatial entity.

4   If any node filtered at point 2 has the *capital* tag equal to *yes*, *1*, *2*, *3*, or *4*, the reference name is marked as capital. If this differs from the main name assigned at point 3, the capital name is concatenated to the main name, between square brackets.

Figure 5. Schematic overview of GHSL SMOD O6 entities workflow logic. "xpop" represents the population density per square kilometre of permanent land; "xbu" represents the built-up density per square kilometre of permanent land.

2.4.5   GHS–SMOD L2 grid and L1 aggregation

Settlement typologies are identified in the GHS-SMOD grid at L2 with a two digit code (30 – 23 – 22 – 21 – 13 – 12 – 11 – 10), linking to grid level and municipal level description terms (both the municipal and grid level terms are accompanied by a technical term). **Classes 30 – 23 – 22 – 21 if aggregated form the "urban domain", 13 – 12 – 11 – 10 form the "rural domain"**. **Error! Reference source not found.**Table 9 shows the L2 grid cells population (expressed as people per square kilometre: people/km²) and built-up area (expressed

as square kilometres: km^2) expected characteristics in terms of min-max population and built-up density bounds. Table 8 presents the logic to define settlement typologies.

The first level (L1) is obtained by aggregation of L2 according to the first digit of the code, as shown in Table 6 and it represents a porting of the EUROSTAT "degree of urbanization".

Table 6 Aggregation of L2 class typologies to L1 class typologies (EUROSTAT DEGURBA model)

30	→	3
23 – 22 – 21	→	2
13 – 12 – 11 – 10	→	1

L1 classifies three settlement typologies as displayed in Table 10. Settlement typologies are identified at L1 with a single digit code (3 – 2 – 1), and grid level and municipal level terms (both the municipal and grid level are accompanied by a technical term), HDC for type 3, MDC for type 2, and LDC for type 1). Classes 3 - 2 if aggregated form the "urban domain", 1 forms the "rural domain". Table 11 presents the logic to define settlement typologies as described in section 2.4.3. Table 12 shows the L1 grid cells population and built-up area characteristics in terms of min-max population and built-up density bounds.

Table 7 Settlement Model L2 nomenclature

Code	RGB	Grid level term	Spatial entity (polygon) *Technical term*	Other cells *Technical term*	Municipal level term *Technical term*
30	255 0 0	URBAN CENTRE GRID CELL	URBAN CENTRE *DENSE, LARGE CLUSTER*		CITY *LARGE SETTLEMENT*
23	115 38 0	DENSE URBAN CLUSTER GRID CELL	DENSE URBAN CLUSTER *DENSE, MEDUM CLUSTER*		DENSE TOWN *DENSE, MEDIUM SETTLEMENT*
22	168 112 0	SEMI-DENSE URBAN CLUSTER GRID CELL	SEMI-DENSE URBAN CLUSTER *SEMI-DENSE, MEDIUM CLUSTER*		SEMI-DENSE TOWN *SEMI-DENSE, MEDIUM SETTLEMENT*
21	255 255 0	SUBURBAN OR PERI-URBAN GRID CELL		SUBURBAN OR PERI-URBAN GRID CELLS *SEMI-DEMSE GRID CELLS*	SUBURBS OR PERI-URBAN AREA *SEMI-DENSE AREA*
13	55 86 35	RURAL CLUSTER GRID CELL	RURAL CLUSTER *SEMI-DENSE, SMALL CLUSTER*		VILLAGE *SMALL SETTLEMENT*
12	171 205 102	LOW DENSITY RURAL GRID CELL		LOW DENSITY RURAL GRID CELLS *LOW DENSITY GRID CELLS*	RURAL DISPERSED AREA *LOW DENSITY AREA*
11	205 245 122	VERY LOW DENSITY RURAL GRID CELL		VERY LOW DENSITY RURAL GRID CELLS *VERY LOW DENSITY GRID CELLS*	MOSTLY UNINHABITED AREA *VERY LOW DENSITY AREA*
10	122 182 245	WATER GRID CELL	-	-	-

Table 8 Settlement Model L2 synthetic explanation of logical definition and grid cell sets

Code	Logical Definition at 1 km² grid cell	Grid cell sets used in the logical definition (shares defined on land surface)			
		P_{dens}: Local Population Density lower bound ">" (people/km²)	P_{min}: Cluster Population lower bound ">" (people)	B_{dens}: Local share of Built-up Area lower bound ">" (km²)	T_{con}: Topological constrains
30	$(((P_{dens} \vee B_{dens}) \wedge T_{con}) \wedge P_{min}) \vee$ $\vee$ [iterative_median_filter(3-by-3)] $\vee$ [gap_fill(<15km2)][12]	1,500	50,000	0.50	4-connectivity clusters
23	$(((P_{dens} \vee B_{dens}) \wedge T_{con}) \wedge P_{min}) \wedge \neg\ 30$	1,500	5,000	0.50	4-connectivity clusters
22	$((((P_{dens} \wedge B_{dens}) \wedge T_{con\_1}) \wedge P_{min}) \wedge \neg\ (30 \vee 23)) \wedge T_{con\_2}$	300	5,000	0.03	1: 4-connectivity clusters; 2: farther than 3km (beyond 3 cells buffer) from 23 or 30
21	$(((((P_{dens} \wedge B_{dens}) \wedge (30 \vee 23)) \wedge T_{con\_1}) \wedge P_{min}) \wedge \neg\ (30 \vee 23)) \wedge T_{con\_2}$	300	5,000	0.03	1: 4-connectivity clusters; 2: within 3km (within 3 cells buffer) from 23 or 30
13	$((P_{dens} \wedge T_{con}) \wedge P_{min}) \wedge \neg\ (30 \vee 2X)$	300	500	none	4-connectivity clusters
12	$P_{dens} \wedge \neg\ (30 \vee 2X \vee 13)$	50	none	none	none
11	$T_{con} \wedge \neg\ (30 \vee 2X \vee 13 \vee 12)$	none	none	none	On Land (Land>=50% $\vee$ BU[13]>0% $\vee$ Pop>0)
10	T_{con}	none	none	none	Not on Land

[12] The seeds for the related spatial entity is obtained before morphological operations
[13] Retaining only contiguous BU at least partially on land.

Table 9 Settlement Model L2 grid cells population and built-up area characteristics (densities on permanent land)

Code	Population		Built-up area	
	Minimum density expected (people/km^2)	Minimum density expected (people/km^2)	Minimum density expected (share)	Minimum density expected (share)
30	0	∞	0	1
23	0	50,000	0	1
22	300	5,000	0.03	1
21	300	5,000	0.03	1
13	300	5,000	0	1
12	50	500	0	1
11	0	50	0	1
10	0	0	0	0

Table 10 Settlement Model L1 nomenclature

Code	RGB	Grid level term	Spatial entity (polygon) *Technical term*	Other cells *Technical term*	Municipal level term *Technical term*
3	255 0 0	URBAN CENTRE GRID CELL	URBAN CENTRE *HIGH DENSITY CLUSTER (**HDC**)*		CITY *DENSELY POPULATED AREA*
2	255 170 0	URBAN CLUSTER GRID CELL	URBAN CLUSTER *MODERATE DENSITY CLUSTER (**MDC**)*		TOWNS & SUBURBS *INTERMEDIATE DENSITY AREA*
1	115 178 115	RURAL GRID CELL		RURAL GRID CELLS *LOW DENSITY GRID CELL (**LDC**)*	RURAL AREA *THINLY POPULATED AREA*

Table 11 Settlement Model L1 synthetic explanation of logical definition and grid cell sets

Code	Logical Definition at 1 km^2 grid cell	Grid cell sets used in the logical definition (shares defined on land surface)			
		P_{dens}: Local Population Density lower bound ">" (people/km^2)	P_{min}: Cluster Population lower bound ">" (people)	B_{dens}: Local share of Built-up Area lower bound ">" (km^2)	T_{con}: Topological constrains
3	$(((P_{dens} \lor B_{dens}) \land T_{con}) \land P_{min}) \lor$ $\lor$ [iterative_median_filter(3-by-3)] $\lor$ $\lor$ [gap_fill(<15km^2)] [14]	1,500	50,000	0.50	4-connectivity clusters
2	$(P_{dens} \land B_{dens}) \land P_{min} \land T_{con} \land \neg 3$	300	5,000	0.03	4-connectivity clusters
1	$(((((P_{dens} \land B_{dens}) \land 3) \land T_{con}) \land P_{min}) \land$ $\land \neg 3^{\S}$	none	none	none	none

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[14] The seeds for the related spatial entity is obtained before morphological operations

Table 12 Settlement Model L1 grid cells population and built-up area characteristics (densities on permanent land)

Code	Population		Built-up area	
	Minimum density expected (people/km^2)	Minimum density expected (people/km^2)	Minimum density expected (share)	Minimum density expected (share)
3	0	∞	0	1
2	0	50,000	0	1
1	0	5,000	0	1

2.4.6 Input Data

The input data are the multi-temporal GHS-BUILT and GHS-POP grids of the GHSL Data Package 2019 (GHS P2019). Land is extracted as a combination of the Global ADMinstrative Map 2.8[15] and the Global Surface Water Layer Occurrence[16]. Names[17] are extracted from OpenStreetMap partially filtered by EUROSTAT (GISCO project[18]).

2.4.7 Technical Details

Author: Martino Pesaresi, Aneta Florczyk, Marcello Schiavina, Luca Maffenini, Michele Melchiorri, Joint Research Centre (JRC) European Commission.

Product name: GHS_SMOD_POP_GLOBE_R2019A

Spatial extent: Global

Temporal extent: 1975-1990-2000-2015

Coordinate System: World Mollweide (EPSG: 54009)

Resolution available: 1 km

Table 13 outlines the technical characteristics of the datasets released in this data package.

2.4.7.1 GHS-SMOD raster grid

Encoding: integer16 [30 – 23 – 22 – 21 – 13 – 12 – 11 – 10], No Data: -200

Data organisation: TIF with CLR colormap (L2_colcod.tif.clr) file as single global layer or tiled.

2.4.7.2 GHS-SMOD Urban Centre entities[19]

Data organisation: GeoPackage (GPKG) database with vector layer of Urban Centre entities boundaries (polygons).

Attributes:

- ID_HDC_G0: Unique Identifiers of the urban centre entity;
- Name_main: Main name assigned to the urban centre entity;
- Name_list: List of all name selected within the spatial entity;
- POP_<year>: sum of GHS-POP within the spatial entity extent for the related year;
- BU_<year>: sum of GHS-BU within the spatial entity extent for the related year

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[15] https://gadm.org/data.html
[16] https://global-surface-water.appspot.com/download
[17] Names assigned do not imply official endorsement or acceptance by the European Union © OpenStreetMap
[18] https://ec.europa.eu/eurostat/web/gisco
[19] This datasets is not comparable with the GHS Urban Centre DataBase v1.x (Florczyk et al., 2019)

Table 13. Technical details of the datasets in GHS_SMOD_POPMT_GLOBE_R2019A

GHS_SMOD_POPMT_GLOBE_R2019A			
ID	**Description**	**Resolution (Projection)**	**Size**
GHS_SMOD_POP2015 _GLOBE_R2019A _54009_1K_V2_0	Settlement typology codes for epoch 2015 NoData [-200]	1 km (World Mollweide)	12 MB
GHS_SMOD_POP2000 _GLOBE_R2019A _54009_1K_V2_0	Settlement typology codes for epoch 2000 NoData [-200]	1 km (World Mollweide)	11.5 MB
GHS_SMOD_POP1990 _GLOBE_R2019A _54009_1K_V2_0	Settlement typology codes for epoch 1990 NoData [-200]	1 km (World Mollweide)	11 MB
GHS_SMOD_POP1975 _GLOBE_R2019A _54009_1K_V2_0	Settlement typology codes for epoch 1975 NoData [-200]	1 km (World Mollweide)	10.5 MB
GHS_SMOD_POP2015 _GLOBE_R2019A _54009_1K_labelHDC_V2_0	2015 Urban Centre entities boundaries	1 km (World Mollweide)	12 MB
GHS_SMOD_POP2000 _GLOBE_R2019A _54009_1K_labelHDC_V2_0	2000 Urban Centre entities boundaries	1 km (World Mollweide)	11.5 MB
GHS_SMOD_POP1990 _GLOBE_R2019A _54009_1K_labelHDC_V2_0	1990 Urban Centre entities boundaries	1 km (World Mollweide)	11 MB
GHS_SMOD_POP1975 _GLOBE_R2019A _54009_1K_labelHDC_V2_0	1975 Urban Centre entities boundaries	1 km (World Mollweide)	10.5 MB

2.4.8 Summary statistics

Table 14 Summary statistics of total area in square kilometres of each settlement typology at global level as obtained from the 1-km GHS-POP grids L2.

	1975	1990	2000	2015
30	306,180	429,229	533,045	665,641
23	207,433	264,360	297,206	331,558
22	111,003	128,511	139,167	154,801
21	421,746	593,198	698,790	823,614
13	818,744	937,466	1,020,680	1,163,761
12	2,832,956	3,221,002	3,558,714	4,024,084
11	140,982,705	140,099,083	139,420,665	138,504,904

Table 15 Summary statistics of total built-up area in square kilometres for each settlement typology at global level as obtained from the 1-km GHS-POP grids L2.

	1975	1990	2000	2015
30	13,023,407	19,163,076	24,892,506	30,005,410
23	4,973,363	6,706,174	7,945,364	8,796,052
22	1,921,714	2,380,061	2,734,640	3,033,187
21	6,270,036	8,940,169	11,002,298	13,449,073
13	4,192,598	5,402,874	6,328,978	7,107,380
12	5,722,583	7,332,990	9,421,017	12,123,285
11	1,851,377	2,407,680	3,249,061	4,423,226

Table 16 Summary statistics of total population in each settlement typology at global level as obtained from the 1-km GHS-POP grids L2.

	1975	1990	2000	2015
30	1,517,602,834	2,211,665,840	2,721,263,070	3,544,107,384
23	847,910,186	1,062,883,725	1,150,518,125	1,246,207,360
22	101,905,977	118,917,179	129,745,641	141,509,191
21	354,038,947	503,932,173	590,913,476	689,211,502
13	714,554,953	825,388,867	891,416,995	1,009,601,490
12	412,707,214	476,210,241	532,137,585	604,474,198
11	112,628,245	110,598,981	110,534,315	114,217,925

Table 17 Summary statistics of total area in square kilometres of each settlement typology at global level as obtained from the 1-km GHS-POP grids L1.

	1975	1990	2000	2015
3	306,180	429,229	533,045	665,641
2	740,182	986,069	1,135,163	1,309,973
2	648,429,638	648,060,702	647,807,792	647,500,386

Table 18 Summary statistics of total built-up area in square kilometres for each settlement typology at global level as obtained from the 1-km GHS-POP grids L1.

	1975	1990	2000	2015
3	13,023,407	19,163,076	24,892,506	30,005,410
2	13,165,112	18,026,405	21,682,301	25,278,312
2	11,766,728	15,143,820	18,999,470	23,654,835

Table 19 Summary statistics of total population in each settlement typology at global level as obtained from the 1-km GHS-POP grids L1.

	1975	1990	2000	2015
3	1,517,602,834	2,211,665,840	2,721,263,070	3,544,107,384
2	1,303,855,109	1,685,733,077	1,871,177,242	2,076,928,054
2	1,239,890,413	1,412,198,089	1,534,088,895	1,728,293,613

2.4.9   How to cite

Dataset:

Pesaresi, Martino; Florczyk, Aneta; Schiavina, Marcello; Melchiorri, Michele; Maffenini, Luca (2019): GHS settlement grid, updated and refined REGIO model 2014 in application to GHS-BUILT R2018A and GHS-POP R2019A, multitemporal (1975-1990-2000-2015), R2019A. European Commission, Joint Research Centre (JRC) [Dataset] doi:10.2905/42E8BE89-54FF-464E-BE7B-BF9E64DA5218 PID: http://data.europa.eu/89h/42e8be89-54ff-464e-be7b-bf9e64da5218

Concept & Methodology:

Florczyk, Aneta J.; Corbane, Christina; Ehrlich, Daniele; Freire, Sergio; Kemper, Thomas; Maffenini, Luca; Melchiorri, Michele; Pesaresi, Martino; Politis, Panagiotis; Schiavina, Marcello; Sabo, Filip; Zanchetta, Luigi (2019): GHSL Data Package 2019, EUR 29788 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-13187-8 doi:10.2760/0726, JRC 117104

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