

GLOBAL HUMAN SETTLEMENT ANALYSIS FOR DISASTER RISK REDUCTION

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ABSTRACT:

The Global Human Settlement Layer (GHSL) is supported by the European Commission, Joint Research Center (JRC) in the frame of his institutional research activities. Scope of GHSL is developing, testing and applying the technologies and analysis methods integrated in the JRC Global Human Settlement analysis platform for applications in support to global disaster risk reduction initiatives (DRR) and regional analysis in the frame of the European Cohesion policy. GHSL analysis platform uses geo-spatial data, primarily remotely sensed and population. GHSL also cooperates with the Group on Earth Observation on SB-04-Global Urban Observation and Information, and various international partners and World Bank and United Nations agencies. Some preliminary results integrating global human settlement information extracted from Landsat data records of the last 40 years and population data are presented.

1. INTRODUCTION

Global actors and global decision making processes need accurate and globally consistent data for evidence-driven reasoning: testing of hypothesis, development of concepts, monitoring and understanding of trends, and exploration of alternative scenarios. Space and airborne remote sensing technologies have contributed since the 60 of the last century to make consistent data series describing the physical characteristics of the global atmosphere, ocean and land masses. Census surveys techniques reporting about the amount of population, houses and productive activities have more than 5,000 years history dating back to the origin of the state and urban social organization of the humanity. The same can be affirmed about cadastral and geometrical land surveys techniques that have been an essential element in the development of the human environment since the beginning of recorded history. Taking apart hunter and gathering societies, today the absolute majority of human beings spend the dominant part of their life time in built artificial environment supporting by different means both their symbolic-cultural and practical-functional necessities. From the material and practical point of view, this artificial environment includes closed built-up structures and their open neighborhood spaces as roads, squares, gardens. The whole above can be shortly described as belonging to the basic, physical or material elements of the human settlement.

The understanding of the global human settlements is absolutely critical for a large number of issues including housing and urban development, poverty reduction, sustainable development, climate change, crisis management and disaster risk reduction, just to name a few. But despite their importance and despite the long history of human development in the surveys techniques, apparently basic questions about global human settlements still remain unanswered, as for example: how many square/cubic meters we have built in the last 40 years?, what are the specific spatial-temporal trends and patterns?, what are the occupancy conditions and density of persons in these spaces? and similar. Detailed human settlement data collected by census surveys techniques are very local, expensive then rare, and difficult to harmonize globally. Consequently large inconsistencies and large data

gaps are existing at global level inherited from different national standards, nomenclature and resource availability for census data collection. The definition of what is considered an urban area can vary from *localities of 200 or more inhabitants* (Iceland) to *settlements having 50 000 or more inhabitants with 60 per cent or more of the houses located in the main built-up areas and 60 per cent or more of the population (including their dependents) engaged in manufacturing, trade or other urban type of business* (Japan) with a whole range of single national-specific heterogeneous conditions in between¹. Similar and even more challenging issues are related to fine-scale land surveys and cadastral data: they are very expensive to be produced, collected and managed: from the global surface perspective, they are a rarity rather than the normality. Recent developments on crowd-sourcing and fine-scale cartographic open data collection as the Open Street Map²(OSM) project may contribute to the general picture, but they are far from the necessary completeness and consistency needed for global decision making processes.

Broad-scale land surveys using standard remote sensing technologies have demonstrated the capacity to map the global landmass with a sustainable cost in several application domains, but the map of the global human settlement is still largely incomplete. Available global surveys provide total accounted settlement surfaces that can vary up to one order of magnitude (Potere et al., 2009). The global bias and gain functions associated to the different sensors and information retrieval methods are still largely unknown, as regarding the detection of basic components of the humans settlements: houses, roads, and open spaces. In particular, the detection of these components with different background surfaces and landscape patterns combinations, in a representative set of the heterogeneous fine-scale cases available in the globe. As a consequence, global remote-sensing derived information about human settlements risks to inject large indeterminacy and systematic uncontrolled bias in the models assuming these information in input. Moreover, as other consequence, so

¹United Nations Statistics Division, Notes on table Table 6 *Total and urban population by sex* - Demographic Yearbook 2012 <http://unstats.un.org/unsd/demographic/products/dyb/dyb2012/notes/notes06.pdf>

²www.openstreetmap.org

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Figure 1: Example of the European settlement information extracted by the GHSL platform from Spot 2.5-m resolution input imagery in Athens (Greece). Top: input image. Bottom: output of the automatic data classification. Dark brown: built-up areas (buildings), green: vegetated open spaces, white: other open spaces

far remote sensing technologies have demonstrated a very limited capacity to map the spatial evolution of the global human settlements, involving the integration of a variety of sensors and data classification approaches linked with unknown mutual systematic bias/gain functions.

The density, the heterogeneity, the dynamics of human settlements and their interactions with the environment are fundamental pieces of information we need to have at hand to help us keep in balance the use and regenerative capacity of our planets resources. But the current picture of the human footprint is incomplete. The majority of small and medium-sized settlements, critical for accounting and understanding the impact of people on the globe, remain largely invisible. The big dots may be visible, but not the all-important connections between them. And the truly vulnerable, such as those dwelling in refugee camps, shantytowns and slums are effectively missing from our global understanding³. The aim of the GHSL project is to contribute to fill these information gaps exploiting remote sensing technologies. In particular, GHSL aims to contribute to a the global assessment of human settlement surfaces and their spatial dynamics, using

fine-scale remote sensing data (Pesaresi and Ehrlich, 2009, Pesaresi et al., 2011, Pesaresi et al., 2013). Extensive tests using the Landsat data archive of the last 40 years have been conducted during 2014: some first results combining human settlement information extracted from satellite data and population data are showed here.

2. FINE-SCALE REMOTE SENSING OF GLOBAL HUMAN SETTLEMENTS

Despite the large potential of today's remote sensing technologies, concrete attempts to create fine-scale information layers reporting about human settlement at the date are only few. On the active remote sensing technology, published examples so far include a method aiming to produce *global urban area extent* using ASAR 75-m-resolution input data (Gamba and Lisini, 2012) and a method aiming to produce *global urban footprints* using finer resolution TanDEM-X data (Esch et al., 2013): while very promising, and based on input data with available global coverage, these technologies dont have provided yet a global complete classification test. On the passive remote sensing technology, a method aiming to *global urban area mapping* integrating ASTER data at 15m-resolution with extensive GIS data used in post-processing and information masking was proposed in by (Miyazaki et al., 2013). General issues related to these methods are i) the adoption of fixed cut-off in the feature space that are difficult to apply globally and independently from the background landscape or data collection parameters and ii) the adoption of rigid rule-based data masking strategies in the post-processing phase, in order to improve the accuracy of the classification output. Post-classification data masking strongly increases dependency of the satellite data classification output with third-parties sources: consequent strongly decreases the value added of satellite-derived information.

First examples of systematic, sample-based analysis of global urbanization using Landsat data include the processing of 120 cities for two epochs (1990, 2000) (Angel et al., 2005) and a systematic analysis of 27 current mega cities using multi-temporal Landsat data (years 1975,1990,2000) coupled with TerraSar-X data (year 2010) that was presented in (Taubenböck et al., 2012). The first documented trial to generate global land cover by automatic classification of Landsat input data is the production of the Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) as reported in (Gong et al., 2013). In FROM-GLC only one epoch (circa 2006) was processed, and the the *impervious* surfaces resulted with not satisfactory classification accuracy (Ban et al., 2015, Gong et al., 2013). Successive experimental activity tried to inject in FROM-GLC output the *urban* or *impervious* information derived from third-parts, low-resolution satellite-derived information sources (Yu et al., 2014). Finally, a 30-m-resolution global land cover (GlobeLand30) was produced as reported in (Chen et al., 2014). GlobeLand30 process two global Landsat data collections (years 2000 and 2010), it integrates in the output several internationally available land cover products, and relies on large use of manual editing of the final maps done by domain experts (Chen et al., 2014). General issues related to the above methods are i) the relevant cost allocated to manual operations still needed including training set collection, data processing parameters tuning and output editing ii) the large computational cost of the adopted supervised classifiers. These issues risk to produce prohibitive costs in porting these methods to global multi-temporal, fine-scale data classification scenarios.

³GEO (Group on Earth Observations), Statement for a Global Human Settlement Partnership 2014 https://www.earthobservations.org/documents/ghs/ghs_brochure.pdf



Figure 2: Example of built-up areas extracted from Landsat data processing in the GHSL workflow in the Veneto region (Italy). Top: high resolution image of a scattered settlement pattern. Bottom: output of the automatic recognition of built-up areas using 30-m-resolution input Landsat data.

3. THE GHSL PROJECT

The Global Human Settlement project (GHSL) is supported by the European Commission, Joint Research Centre with the objective to design and test new technologies able to generate global fine-scale representations of the physical characteristics of the human settlements. In particular, the GHSL project is focused on innovative automatic image information extraction processes, using metric and decametric scale satellite data input (Pesaresi et al., 2013). The target information collected by the GHSL project is the built-up structure or building, aggregated in built-up areas and then settlements according to explicit spatial composition laws. They are the primary sign and empirical evidences of human presence on the global surface that are observable by current remote sensors. As opposed to standard remote sensing practices based on *urban land cover* or *impervious surface* notions, the GHSL semantic approach is continuous quantitative and centered around the presence of buildings and their spatial patterns: thus making the information gathering independent from any rural / urban prior abstract definition (Pesaresi and Ehrlich, 2009). The GHSL project assumes an inclusive concept of the *building*, including temporary structures observable in refugees and internally displaced people (IDP) camps, and poor structures of shanty towns and slums. From the GHSL methodological perspective, automatic information gathering processes are the necessary conditions for sustainable global detailed surveys, but also

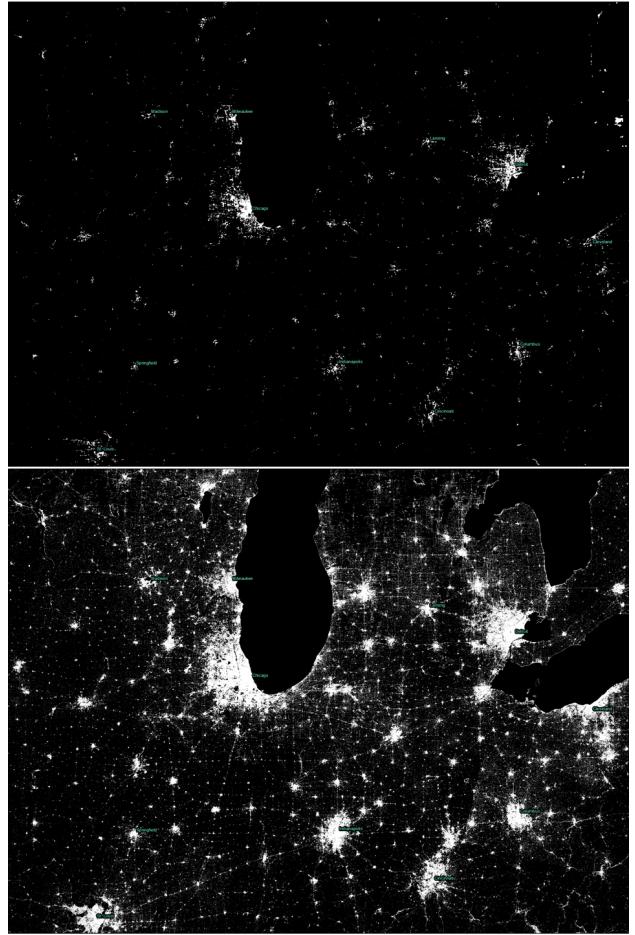


Figure 3: Comparison of the human settlement information extracted from satellite sensors at different spatial resolution in the area of Chicago-Detroit (US). Top: *artificial surfaces* as reported by the ESA GlobCover using 300-m-resolution MERIS satellite imagery. Bottom: *built-up areas* as reported by the JRC GHSL using 30-m-resolution Landsat satellite data

for the reproducibility and public control of the information, thus contributing to the objectivity and evidence-based support to the decisional processes. Because of the institutional mandate of the project, the core scope of the human settlement theme proposed here is to support the global security and crisis management (GSCM) applications domains with global, fine scale information (Pesaresi et al., 2010, Freire et al., 2014, Freire et al., 2015a, Freire et al., 2015b, Florczyk et al., 2015a). In these applications, physical characteristics of the settlements - as number of buildings, their surface, their typology (size, high) and spatial patterns - are important information supporting decisions with large social and economical impact. This information typically supports activities as damage and reconstruction assessment, impact assessment, disaster early warning and alerting, losses estimates, exposure and risk mapping and post-disaster need assessment (PDNA), just to mention a few. From the above perspective, Remote Sensing (RS) data is potentially an interesting source because independent, globally-consistent, updated, synoptic, and objective. This is especially true for global actors involved in GSCM as World Bank, United Nations agencies and other governmental bodies that need to operate globally and multilaterally with standardized and internationally comparable models, even in areas where few or no fine-scale information are provided by the local authorities.

In (Pesaresi et al., 2013) the capacity to discriminate built-up areas was demonstrated with optical sensors in the spatial resolution range of 0.5m-10m and an extensive test set including more than 50 millions of square kilometers of mapped surface. The same system was successfully applied using 2.5-m input sensor resolution for producing large national coverages in Brazil (Kemper et al., 2013) and China (Lu et al., 2013) using CBERS-2B panchromatic data, and continental coverage in Europe (Ferri et al., 2014, Florczyk et al., accepted 2015b) using Spot-5,6 multi-spectral pan-sharpened data. Figure 1 shows an example of the human settlement information extracted by these technologies. To date, these experiments are the largest and most general known attempts to apply automatic data classification techniques for mapping built-up areas using this class of image data in input. A new inter-scale inter-sensor machine learning methods was introduced by (Pesaresi et al., 2013) in the discrete classification field. The aim of the method is to substitute the expensive expert-driven train set data collection with systematic access to open source spatial information already collecting proxies (by scale, by thematic contents) of the information under request. Similar approach in the continuous classification field was independently proposed by (Sexton et al., 2013) for solving the problem of estimating Global, 30-m resolution continuous fields of tree cover. These learning methods work in the scenario where the whole data universe under processing is labeled by one or more training set data. The approach assumes that modern technology allows researchers to analyse the whole population rather than just inspecting a smaller sample: N , the number of observations in the sample, is equal to all (Mayer-Schönberger and Cukier, 2013). This approach was demonstrated robust against large errors in the training set induced by scale generalization and/or omission, commission errors in the data sources: thus allowing to substitute the expert-driven classification parameter tuning with adaptive optimization techniques automatically estimating the best parameters in the specific scene under process. Similar approach can be used for consistency optimization of the global fine-scale information mosaics (Syrris and Pesaresi, 2013), training semi-supervised classifiers (Li et al., 2014), and image enhancement for optimization of image feature extraction (Syrris et al., Accepted 2015).

While these methods can technically solve global or continental fine-scale mapping scenarios, a data policy access problem still remains: to date no global open and freely accessible data is available in the spatial resolution of 0.5m-10m. Satellite data of this class typically fall inside security and commercial use restrictions: use licenses are negotiated as per-project budget and conditions, and are difficult to share in the broader global scientific community. On-line image streaming platforms distributing global fine-scale data repositories as Bing, Google, Esri can already provide input data suitable for the GHSL automatic image information extraction workflow, but various commercial restrictions are applied for processing the image data on the client side, and on the volume of the image data tiles that can be freely downloaded. During 2014, and extensive experimentation aiming to port the GHSL production system from the 0.5m-10m to the 10m-75m resolution range was undertaken. The latter range matches the resolution of today's available global, open fine-scale satellite data as Landsat and Sentinel. Successful GHSL production in this spatial resolution range would allow the production of global open human settlement information freely sharable in the scientific and user community. Free and open data access policy is an important value added for remote-sensing applications, facilitating the sharing of the analysis results in the global scientific and user communities, thus augmenting their societal impact and benefit (Wulder and Coops, 2014). In particular, two main streams of experimentation are implemented in the GHSL

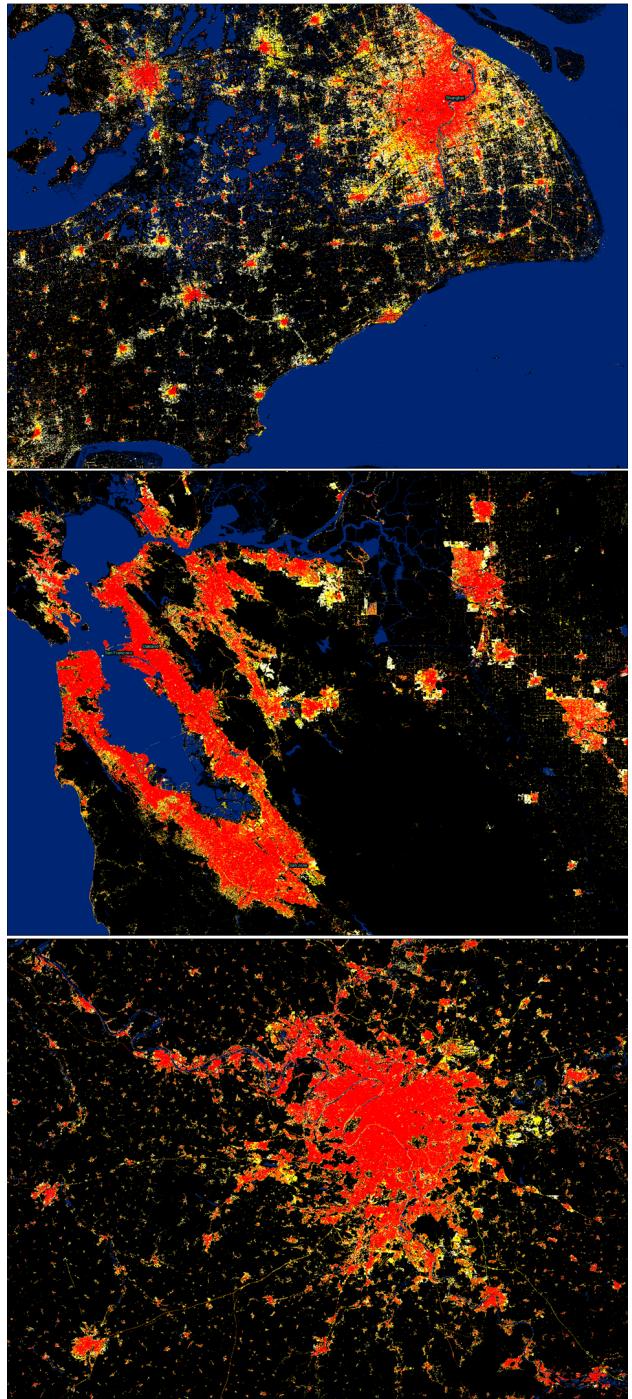


Figure 4: Examples extracted from the ALPHA release of the GHSL Landsat Multitemporal. From top to the bottom: Shanghai, San Francisco, and Paris. In red built-up areas detected before 1975. Orange, yellow, and white encode the built-up areas detected in the 1990, 200, and 2014 epochs

project: i) test archived Landsat data for historical GHSL information retrieval, and ii) test Sentinel 1,2 data for continuous GHSL update. The GHSL Landsat prototype is planned by end 2015, while the GHSL Sentinel1,2, and integrated prototype is planned by 2015,2016 and 2017 respectively. The alpha prototype of the GHSL Landsat was released in October 2014 and shared among the user community for early testing activities. The prototype processed global Landsat data of the years 1975, 1990, 2000, and 2014 with an input spatial resolution ranging from 75

to 15 meters. Figure 2 shows the output of the automatic recognition of built-up areas as implemented in the alpha release of the Landsat GHSL. The concept of Human Settlement adopted in this study relay on the classical notion inherited from the settlement geography, defined as "...the description and analysis of the distribution of buildings by which people attach themselves to the land." (Stone, 1965). The building is the basic sign of the human presence that can be physically observable by remote sensing technologies. Consistently with the above approach, the whole classes of settlement used in this study are derived by spatial generalization of the basic information about the presence of the building, as detected by the available remotely sensed data. The *building* are constructions above ground which are intended or used for the shelter of humans, animals, things, the production of economic goods or the delivery of services. The working definition above is a thematic characterization of the *building* class as defined by the Infrastructure for Spatial Information in Europe (INSPIRE) standard (Infrastructure for Spatial Information in Europe, 2011). In particular, respect to INSPIRE, the *underground* building case was excluded and the *permanency* of built-up structures condition was violated (Pesaresi et al., 2013). The reason of the first change is clearly related to the limit of the adopted remote sensing technology, while the second is related to the application domain. Global security and crisis management applications often require to monitor temporary or semi-permanent settlements as refugee camps, but also informal and poor built-up structures not falling inside the standard *building* class. The *built-up area* BU_{Ψ} is the set of all the spatial units collected by the specific sensor-information-model Ψ and containing a building or part of it. The sensor-information-model Ψ embeds the spatial detail (scale) of the sensor used to extract the thematic information, and the thematic detail (information sensitivity and specificity) allowed by the adopted information extraction method coupled with the available input data characteristics.

Figure 3 shows the comparison of the human settlement information extracted from satellite sensors at different spatial resolution in the area of Chicago-Detroit (US). At the top the *artificial surfaces* as reported by the ESA GlobCover⁴ using 300-m-resolution MERIS satellite imagery. At the bottom it is showed the *built-up areas* as reported by the JRC GHSL using 30-m-resolution Landsat satellite data input. It is evident the gain of new information discovered by finer resolution sensors and advanced data classification techniques. Figure 4 shows the output of the multitemporal information encoded in the GHSL Landsat in three large cities: from top to the bottom Shanghai, San Francisco, and Paris. In red the built-up existing before the 1975. Orange, yellow and white are encoding the 1990, 2000, and 2014 years.

4. THE GEO WORKING GROUP

The JRC GHSL project supports the Global Human Settlement Working Group (GHS WG) in the frame of the Group on Earth Observations (GEO). The scope of the GHS WG is to contribute the GEO task SB-04-C1: Global Urban Observation and Information by establishing and fostering a new community of practices focused on specific goals. In particular, testing the production and the use of new global human settlement information products derived by integration of global remote sensing data, environmental data, population and socio-economic data analysis. The scope is global and multidisciplinary, with a particular emphasis on testing the use and integration of new global fine-scale information products made available by development of the remote sensing technology and the establishment of open public data access policies. The GHS WG is committed to develop a

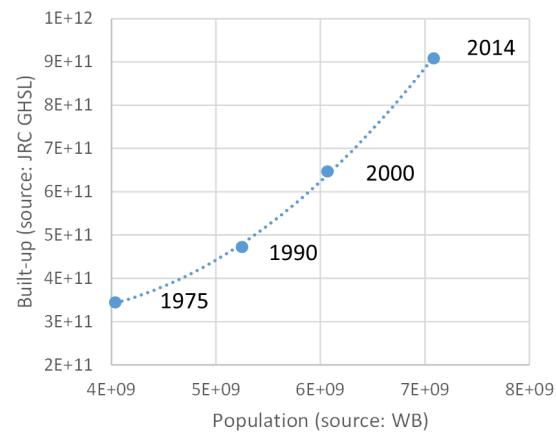


Figure 5: Global population and built-up areas evolution in the last 40 years. The fine-scale built-up areas are estimated by the JRC GHSL using Landsat input imagery

new generation of measurements and information products assessing new scientific evidences about global human settlement, and supporting global policy processes with agreed, actionable and goal-driven metrics. In particular, the GHS WG is committed to support the UN Third Conference on Housing and Sustainable Urban Development (Habitat III, 2016), the concurrent post-2015 processes on sustainable development, the UN Framework Convention on Climate change and the Hyogo framework for disaster risk reduction.

One important GHS WG objective is to improve the sharing of tools and data in the different expert domains. In October 2014, JRC decided to share among the partners of the working group the alpha release of GHSL Landsat for early testing and model integration activities before the official release planned in 2016. This new information layer was extracted from Landsat global data records of the last 40 years (1975-2015) through the porting of the GHSL production workflow in the 10m-75m input image resolution range. To date, the user application list of the fine-scale GHSL information includes population spatial modeling, census planning, poverty mapping, slum mapping, regional development and planning, transport planning, urban and global climate modeling, spatial epidemics analysis, water analysis, ecological studies, environmental protection, agricultural fragmentation studies, and historical landscape protection. Their geographical scope may include national, regional/continental, and global coverages as well.

Some preliminary results integrating information extracted from satellite data and population census data are reported here. Figure 5 shows the aggregated global results of population and built-up areas in the years 1975, 1990, 2000 and 2014 as extracted from the World Bank Open Data⁵ and the JRC GHSL sources, respectively. It is evident that population and built-up areas are linked by direct relations, with global built-up areas growing more rapidly respect the population growth. This is an empirical evidence that globally we are increasing the amount of built-up space pro-capita. The built-up areas pro-capita can be linked to the land-use efficiency and socio-economical development, demanding proportionally more built space for housing and services. Such dynamical data will be crucial input for understanding and modeling the evolution of the human settlements in the next years. It is evident that the global trend showed in the Figure 5 averages a

⁴http://due.esrin.esa.int/page_globcover.php

⁵<http://data.worldbank.org>

multiplicity of heterogeneous local situations. Figure 6 shows the estimated amount of built-up area pro-capita in the years 1975, 1990, 2000, and 2014 in the Countries with more than 50 millions of inhabitants. It is evident the large global disparity and socio-economical divide between the two extrema of the list: namely the 560 square meters of built-up area per inhabitant in US and the 12 square meters of built-up area pro-capita in Bangladesh. Such data can potentially support the definition of globally-consistent and evidence-based indicators contributing to the monitoring of international policy processes as Sustainable Development Goals (SDGs) and Disaster Risk Reduction (DRR).

NAME	1975	1990	2000	2014
United States	321.82	390.45	472.74	560.94
Russia	160.92	205.54	278.69	356.90
Germany	151.48	207.38	267.73	355.51
France	156.87	206.20	267.50	329.58
Italy	112.30	156.09	214.02	271.97
United Kingdom	124.31	161.03	201.00	221.88
Turkey	114.20	118.95	144.80	186.11
Japan	88.91	107.45	135.95	183.49
South Africa	141.48	143.30	153.35	174.92
Brazil	163.93	140.93	166.95	173.90
Mexico	106.96	112.21	131.81	151.12
Indonesia	94.95	83.90	95.26	114.37
Burma	44.00	44.98	53.04	86.81
Iran	65.18	55.09	64.28	84.90
Thailand	45.56	47.17	52.16	84.07
China	38.54	43.45	54.76	83.54
Dem. Rep. Congo	83.29	75.83	77.90	69.89
Vietnam	35.32	34.16	37.70	62.65
Korea, South	33.48	38.56	47.31	61.93
Nigeria	31.69	30.75	33.23	39.93
Egypt	25.25	25.67	29.52	39.70
Philippines	26.20	24.23	25.95	36.80
Ethiopia	30.01	29.00	29.34	33.88
India	17.44	17.13	19.37	32.56
Pakistan	20.41	16.86	17.11	26.56
Bangladesh	6.54	5.76	6.13	12.30

Figure 6: Estimated amount of built-up area pro-capita in the years 1975, 1990, 2000 and 2014 in Countries with more than 50 millions of inhabitants.

5. CONCLUSIONS

A presentation of the Global Human Settlement Layer (GHSL) project was made. The project has the objective to design and test new technologies able to generate global fine-scale information about the physical characteristics of the human settlements. In particular, automatic remote sensing data classification techniques are applied. The project contributes directly to the disaster risk reduction (DRR) international policy processes, but several other application areas need fine-scale Global Human Settlement information. Some examples are provided on the information extracted from satellite data by the GHSL project, including preliminary results obtained from the processing of the global Landsat archived data in the last 40 years in order to understand global human settlement evolution. The JRC GHSL project supports the Global Human Settlement Working Group (GHS WG) in the frame of the Group on Earth Observations (GEO). The GHS WG is committed to develop a new generation of measurements and information products assessing new scientific ev-

idences about global human settlement, and supporting global policy processes with agreed, actionable and goal-driven metrics. In particular, the GHS WG is committed to support the UN Third Conference on Housing and Sustainable Urban Development (Habitat III, 2016), the concurrent post-2015 processes on Sustainable Development (SDG), the UN Framework Convention on Climate change and the Hyogo framework for Disaster Risk Reduction (DRR).

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