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Page: 33 - 38
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Understanding Current Trends in Global Urbanisation - The World Settlement Footprint Suite

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Abstract

To improve the understanding of current trends in global urbanisation, we have launched the World Settlement Footprint (WSF) suite, a collection of novel datasets aimed at providing accurate, reliable and frequent information on the location and extent of human settlements, as well as on their morphology and built-up density. In this paper, we present three of its products (i.e., the WSF-Evolution, WSF2019 and WSF3D), which are expected to become an asset for national statistical offices, local authorities, academia, civil society, private sector, geospatial information community, as well as international organisations involved in the implementation of the Sustainable Development Goal 11 of the United Nations and the New Urban Agenda.

Keywords: global urbanisation, settlement extent, settlement growth, building height, world settlement footprint

1 Introduction

The Sustainable Development Goal (SDG) 11 of the United Nations (UN) aims at renewing and planning human settlements in a way that offers opportunities for all, including access to essential services, transportation, green public spaces, housing and energy, while reducing the impact on the environment and the use of the resources. In this context, accurate, reliable and frequent information is needed on the location and extent of human settlements and their morphology and built-up density. To this purpose, the increasing availability of Big Earth data (as from satellite observations) and related analytics tools (e.g., Artificial Intelligence) has recently opened unprecedented opportunities. However, in the last few years, this has led to the generation of several global layers, primarly focusing only on delineating the actual settlement extent, sometimes with low quality.

To overcome this limitation, the German Aerospace Center (DLR) in collaboration with the European Space Agency (ESA) and the Google Earth Engine team has been generating the World Settlement Footprint (WSF) suite, an unprecedented collection of global datasets aimed at advancing the understanding of urbanization at the planetary scale. In this framework, the first layer to be completed and released open-and-free has been the WSF2015, a 10m resolution binary mask outlining the 2015 global settlement extent derived by jointly exploiting multitemporal optical Landsat-8 and radar Sentinel-1 (S1) imagery (Marconcini et al., 2020). This will be soon followed by other three products, namely

1) The WSF-Evolution, which outlines the global settlement growth at 30m resolution on a yearly basis from 1985 to 2015;
2) the WSF2019, which outlines the 2019 global settlement extent at 10m resolution; and
3) the WSF3D, which estimates the average height of built-up areas globally at 90m resolution.

In the following, an overview is presented of these three layers, which are expected to become an asset for a variety of end users in the framework of several thematic applications, helping to support the achievement of SDG11, as well as the New Urban Agenda.

2 The WSF-Evolution

To effectively foster the sustainable development of human settlements, information on their actual extent is relevant but not sufficient. Indeed, for characterising ongoing trends, a proper understanding of past growth is also necessary. In this framework, a few global layers already exist; nevertheless, they are available for a limited number of time steps and mostly exhibit quite poor quality (as by simple visual comparison versus historical Google Earth imagery). To overcome this drawback, we have implemented a novel iterative approach that - given the lack of suitable archived high-resolution radar imagery - effectively outlines the past settlement extent based on Landsat data alone, acquired globally from late 1984 at 30m resolution.

Initially, we extract - out of all available corresponding Landsat scenes - the minimum, maximum, mean and standard deviation over time per pixel of different spectral indices for each year in the past. These include the normalised difference vegetation index - NDVI, the normalised difference built-up index - NDBI and the modified normalised difference water index - MNDWI. Next, starting from 2015 by using the WSF2015 as reference, we iteratively extract settlement and non-settlement training samples for the year t by: i) adaptively thresholding the corresponding temporal mean NDVI, NDBI and MNDWI; and ii) employing morphological filtering to the settlement mask generated for the year $t+1$. Supervised Random Forest classification is finally applied over the sole pixels marked as settlement at time $t+1$. It is worth noting that, in this way, we cannot address the cases where settlement shrinking occurs; nevertheless, this is a considerably minor phenomenon compared to the ongoing global urbanisation, and it is mainly confined locally.

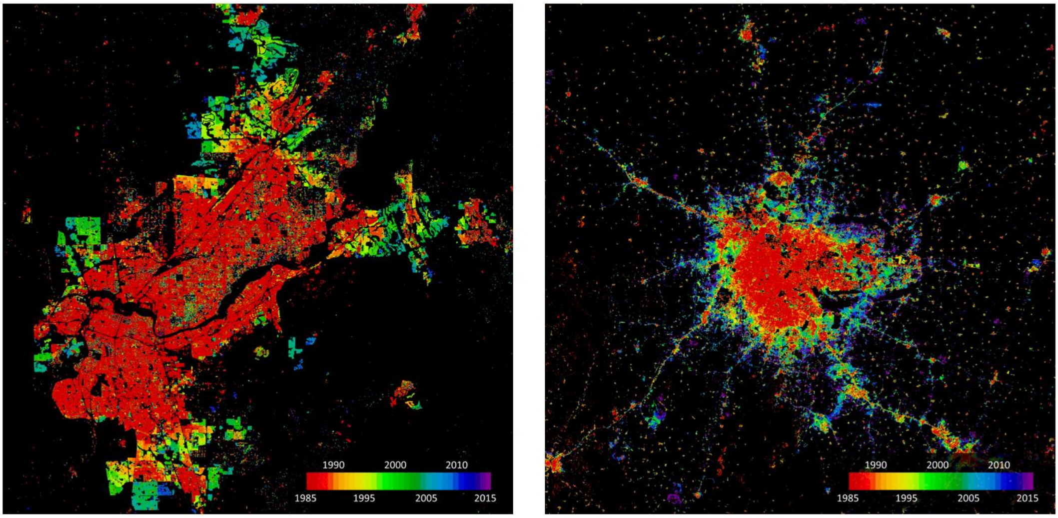

Figure 1: Samples of the 30m spatial resolution WSF-Evolution layer for Sacramento, USA (left) and Bangalore, India (right).

After an extensive test phase, the implemented approach has been eventually employed for generating the WSF-Evolution, i.e. a dataset outlining the global settlement extent at 30m spatial resolution on a yearly basis from 1985 to 2015. Specifically, the entire classification process has been performed on the Google Earth Engine (GEE) platform (Gorelick et al., 2017). Figure 1 shows two samples of the WSF-Evolution for Sacramento (USA) and Bangalore (India), covering an area of ~60x60km and ~80x80km, respectively. To quantitatively assess the accuracy of the dataset, similarly to the case of the WSF2015, an extensive campaign based on crowdsourcing photointerpretation of very high-resolution airborne and satellite Google Earth imagery is currently undergoing. In particular, for the years 1990, 1995, 2000, 2005, 2010 and 2015, ~180K reference cells of 30x30m size distributed over 100 sites worldwide are being labelled, thus summing up to overall ~1M samples.

3 The WSF2019

The advent of Sentinel-2 (S2) in 2015 has marked a milestone in Earth observation. Here, the higher number of spectral bands and higher spatial resolution (i.e., 10-20m) with respect to Landsat data, along with the 5-day revisit time since March 2018, have enabled unprecedented possibilities for monitoring urbanisation. Accordingly, to outline the current global settlement extent, we have implemented a new approach that jointly exploits multitemporal S1 and S2 imagery. Under the hypothesis that settlements generally show a more stable behaviour with respect to all other information classes, temporal statistics are calculated for both S1- and S2-based indices. In particular, a comprehensive analysis has been performed by exploiting a number of reference building outlines to identify a suitable and robust subset, which ultimately resulted in 31 temporal features, including 6 from S1 and 25 from S2. Among others, these include minimum, maximum, mean or standard deviation overtime per pixel of: i) the original radar backscattering in the case of S1, and ii) different spectral indices of S2. As with the WSF2015 and WSF-Evolution, training points for the settlement and non-settlement class are then generated by thresholding specific features (i.e., overall 16 out of the 31 above). In particular, thresholds vary depending on the 30 climate types of the well-established Köppen Geiger scheme (Peel et al., 2007). These have been determined by statistically analysing the distribution of the chosen 16 features within the areas marked as a settlement in the WSF2015. Finally, binary Random Forest classification is applied and a dedicated post-processing is performed to mask out roads by combining the corresponding OpenStreetMap (OSM) layer (OpenStreetMap contributors, 2020) and the novel dataset predicting roads missing from OSM recently published by Facebook (Facebook development team, 2020).

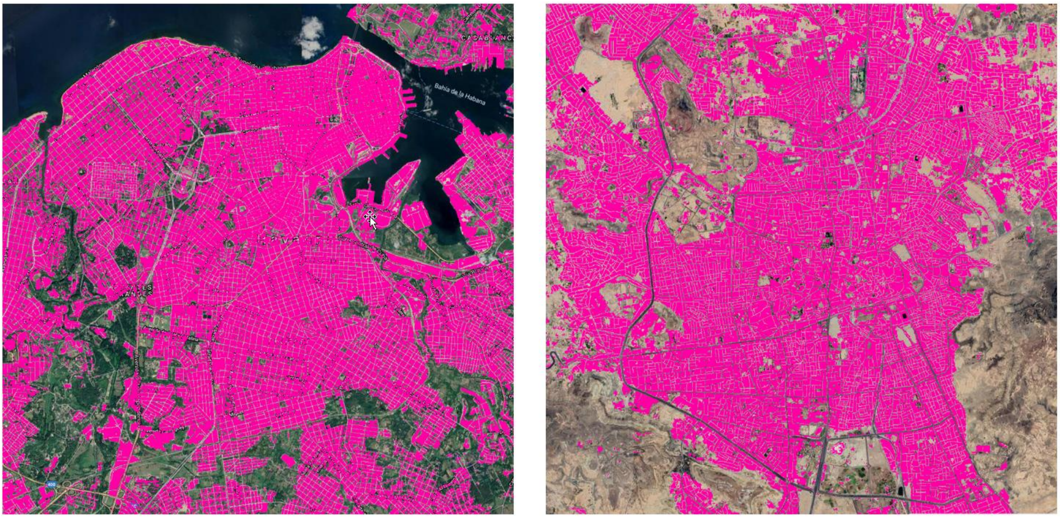

Figure 2: Samples of the 10m spatial resolution WSF2019 layer (in pink) superimposed to Google Earth reference imagery for the cities of Havana, Cuba (left) and Sana'a, Yemen (right).

The method has been tested on a number of study sites throughout the different climate regions and, after assessing its effectiveness (by extensive qualitative comparison against reference Google Earth and Bing Maps imagery), it has been ultimately employed to generate the WSF2019, a novel 10m resolution mask outlining the global settlement extent for the year 2019. Figure 2 reports two samples of the final product of Havana (Cuba) and Sana'a (Yemen), both covering an area of ~10x10km. Also in this case, the whole processing has been performed in the GEE environment, and a dedicated crowd-sourcing-based validation exercise is about to be completed, where ~700K reference labels are being collected based on 2019 VHR imagery available from Google Earth.

4 The WSF3D

Besides a proper delineation of the extent of human settlements, precise information on the building heights is of key importance for better estimating the distribution of the resident population, energy consumption, greenhouse gas emissions, and urban heat island effects or material stock allocation. In this framework, so far, no layer exists, providing a 3D map of the built-up areas globally. To overcome this limitation, we have designed a dedicated methodology, which allows estimating the built-up height by jointly exploiting: the 12m resolution TanDEM-X digital elevation model (TDX-DEM) generated out of TerraSAR-X and TanDEM-X 2012 imagery (Zink et al., 2014), the corresponding 3m resolution original amplitude imagery (TDX-AMP), the WSF2015, as well as S2 and OSM data. In particular, the corresponding workflow consists of three modules. All areas marked as non-settlement in the WSF2015 are excluded a priori from the analysis.

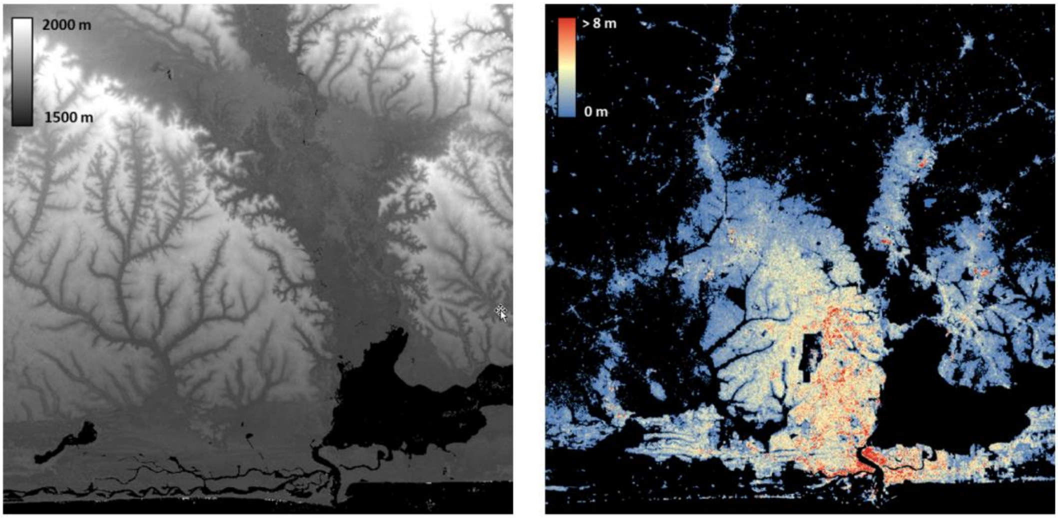

Figure 3: Lagos (Nigeria) – (left) 12m spatial resolution TanDEM-X DEM (TDX-DEM); (right) Sample of the 90m spatial resolution WSF3D average built-up height (BUH) layer.

The first module is dedicated to identifying local vertical edges in the TDX-DEM, whose mean value in a defined 90x90m grid is used for estimating the average building height (BH). Specifically, the generalisation to 90m proved effective in compensating for the effects of building layover. Next, the second module generates a 12m resolution building mask by combining TDX-AMP, OSM and S2 data. Wherever available, building outlines from OSM are used; elsewhere, the TDX-AMP is employed for estimating the location and extent of buildings (Esch et al., 2011). Here, to exclude vertical structures like trees or high hedges present in the built-up environment, a vegetation mask derived from the analysis of the S2 temporal maximum NDVI is also applied. The resulting mask is then used for computing the building fraction (BF) within each cell of the 90m grid above. In the last module, BH and BF are finally merged for estimating the average built-up height (BUH) per 90m cell.

The method has been recently applied globally for generating the WSF3D dataset. In particular, this includes the final BUH, BF and the average built-up volume obtained by multiplying the BUH with the area of the reference 90m cell (i.e., ~8100m² at the equator). As an example, Figure 3 depicts for an area of ~70x70km, including Lagos (Nigeria), both the available TDX-DEM and the corresponding WSF3D BUH. Two parallel exercises are currently aiming to assess the quality of the layer: On the one hand, detailed reference building height information is being gathered for 15 globally distributed regions. On the other hand, the height of more than 150K buildings is being labelled (in terms of the number of floors) by photo-interpretation of Mapillary panorama imagery.

5 Conclusion and Outlook

In this paper, we introduced the WSF-Evolution, WSF2019 and WSF3D layers as part of the WSF suite, aiming to support a comprehensive characterisation of human settlements globally. The three datasets demonstrated particularly accurate and reliable, as confirmed by the highly positive feedback from a number of champion users, who have been yet granted preliminary access to them, namely the World Bank, Asian Development Bank, UN-HABITAT, and International Committee of the Red Cross to cite some. Among others, they proved to be a key resource for analysing urbanisation in developing countries (where often no or poor information is available), supporting the assessment of different SDG 11 indicators, as well as estimating flood exposure or predicting COVID-19 contagion risk. Upon completion of the corresponding quantitative validation activities (expected by mid-2021), all of them are envisaged to be released open and free to the public through multiple resources, including the ESA Urban Thematic Exploitation Platform (U-TEP) and the Geoservice of the Earth Observation Center (EOC) of DLR. As next steps, we already plan: i) to update the WSF-Evolution layer, by using the WSF2019 as a reference and targeting the period 1985-2019; ii) to go beyond the settlement/non-settlement categorisation by generating the WSF2019-Imperviousness, which aims to estimate the settlement per cent soil sealing globally.

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