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Human settlements in low lying coastal zones and rugged terrain: data and methodologies

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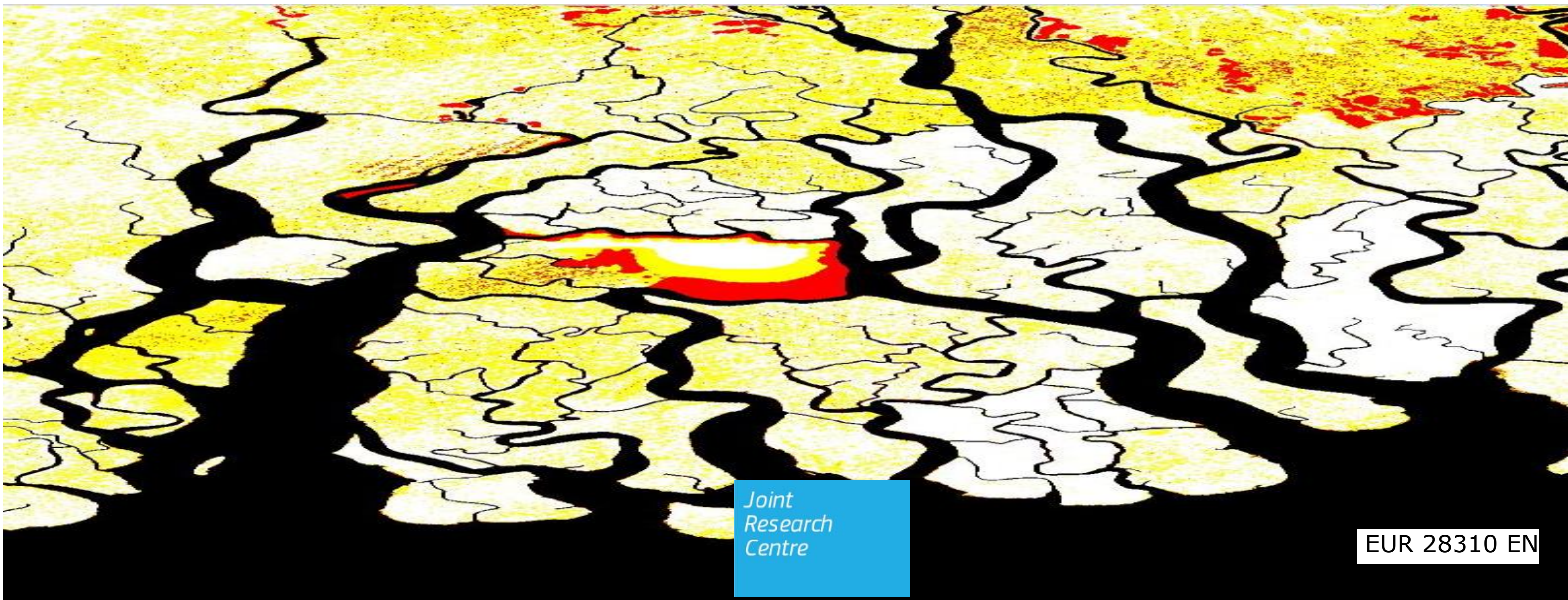

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Abstract

This document describes the assessment of global terrain data and a procedure to combine terrain data with newly available human settlement data. The aim is to quantify settlements in low-lying coastal zones and in topographically rugged terrain. For terrain data we use the Shuttle Radar Topographic Mission Digital Elevation Model made available at 90m (3 arc sec), for settlement data we use the Global Human Settlement Layer (GHSL) data set released in 2016 composed of built-up area (GHS-BU), population (GHS-POP) and settlement model (GHS-SMOD) grids and available for 4 epochs, 1975, 1990, 2000 and 2015. We show that SRTM at 90m and GHSL can be combined in a meaningful way. However, we could not generate accuracy assessment on the resulting figures as both datasets do not come with accuracy assessment. In addition, as the data extend only up to 60degrees north, the analysis is not completely global even if it covers the large part of the populated land masses. Preliminary results show that it is possible to derive quantitative measures related to the increase of population in costal zones, and in steep terrain that may be considered prone to natural hazards. Preliminary analysis indicates that the rate of population growth for the four epochs in the low-lying coastal areas is higher than the global population growth rate. In addition, we show that we are able to measure the spatial expansion of settlements over steep slopes especially in the large cities in developing countries (i.e. Lima), but also in coastal settlements of developed countries (e.g., Italy and France).

1 Introduction

This work aims to evaluate a procedure to measure the global distribution of human settlements with focus on low elevation coastal zone (LECZ- Ramesh et al., 2015) and rugged terrain. We use Shuttle Radar Topography Mission - Digital Terrain Elevation Model (SRTM-DTEM) dataset (Farr et al., 2007) re-processed by the Consultative Group for International Agricultural Research – Consortium for Spatial Information[1] (CIGAR-CSI) into 3 arc second SRTM Version 4.1 (Jarvis et al., 2008). For brevity hereafter we refer to it as SRTM 3 arc sec unless otherwise specified (Figure 1). The focus is to extract 3 LECZ classes and 3 slope classes with focus on steep terrain. Steep terrain analysis aims to explain how gravity can aggravate the effect of the impact of natural hazards. The LECZ classes are used for quantifying exposure to hazardous coastal processes. This is a preliminary analysis that will guide more thorough processing with the availability of improved digital elevation models and finer resolution global human settlement layers.

The global analysis of the distribution of population based on relief started with the availability of global open source digital terrain models. Cohen and Small (1998) analysed the distribution of human population by elevation and latitude. Nicholls and Small, (2002) focussed specifically on population distribution in coastal areas. These early studies combined global population datasets within coastal zones -defined by elevation and distance from the shore. Small and Nicholls, (2003) used as threshold 100m elevation and 100 km distance from the shore and crossed it with the Gridded Population of the Word (GPW Tobler et al., 1995). McGranahan et al., (2007) used 10 m elevation threshold based on an improved SRTM 30 arc sec elevation and a distance of 100 km when elevation bellow 10 m extends into land beyond 100 km. More refined analysis included the use of MODIS-urban (Schneider et al., 2009) to identify the coastal built up with projection of population to 2060. The shortcomings of these earlier works and especially those related to the coarse scale terrain and population data was extensively discussed in (Lichter et al., 2011).

In this work, we define LECZ as land below 10m elevation hydrologically connected to the oceans as per the work initiated by McGranahan et al., (2007). The datum is one order of magnitude better than that of 30 arc sec used in most of the previous studies (Neumann et al., 2015). In addition, the SRTM 3 arc sec dataset allows to mapping coastal areas below sea level that could not be mapped systematically in previous work. This research tests whether SRTM is suitable to subdivide the LECZ in three classes.

The innovation with respect to previous works is also on the use of population and built up information. We use the global population estimates and settlement data based on the Global Human Settlement built up (GHSL-BU) area layers (Pesaresi et al., 2016a) that has a number of advantages. First, the spatial resolution of the GHSL data is one order of magnitude better than that in the earlier studies. Second, the GHSL data package comprises four layers, providing a record of the settlement size in time (circa 1975, 1990, 2000, and 2015) at the global level. Third, the GHSL-BU data have been combined with census data from the respective epochs to derive population densities at 250m grid cells globally (Freire et al., 2015) and providing a spatially disaggregated population grids per each epoch (1975, 1990, 2000, 2015). Population densities, and built up aggregated at different level are used to derive a settlement classification based on population densities and densities of built up that provides a global map of High Density Clusters, and a map of Low Density Clusters (Dijkstra and Poleman, 2014, Pesaresi et al. 2016b).

[1] http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1

2 Data

The Shuttle Radar Topographic Radar Mission (SRTM) aimed to generating a high spatial resolution digital topographic database for the Earth's surface (Farr et al., 2007). The radar data were collected using two antennas separated by a 60-m-long mast using C-band (5.6 cm wavelength) and X-band (3.1 cm wavelength) interferometry synthetic aperture radar (Rabus et al., 2003). The data are available for the entire land masses between 60 North and 50 South into an 1 arc sec grid referred to as Digital Elevation Terrain Model (DETM) (Slater et al., 2006a). Geographically, the SRTM-DTEM dataset is referenced to the WGS84-EGM96 geoid and is geo-referenced in the horizontal plane to the WGS84 ellipsoid. The accuracy requirements for the original 1 arc second were "16 m absolute vertical error (90 per cent linear error, with respect to the reflective surface), 20m absolute horizontal error, 90 per cent circular error and 10 m relative vertical error" (Slater et al., 2006a).

Radar imaging from space platforms is well suited to capture Earth's surface topography, however, there are a number of limitations. There are scattering effects that create spikes when buildings act as corner reflectors, imaging shadows in steep mountain terrain as well as layover effects. In fact, the data were processed to correct for the many errors in a number of ways. In addition, the Radar recordings measure the elevation of the land including the height of the landscape objects. For example, in cities the sensor captures the height of the buildings and in closed forest the height of top of the canopy. SRTM data have been post-processed in a number of ways. Below a succinct list of improvements to datasets that directly or indirectly were used in this research.

- NASA-JPL (NASA) aggregated – by averaging - the original 1 arc sec to 3 arc-sec to produce what eventually became the NASA finished product referred to as NASA-SRTM 2.1. The product was made available from download through USGS website (Merryman Boncori, 2016; Robinson et al., 2014).
- National Geographic Agency (NGA) also processed original 1 arc sec dataset as follows. a) Detected and reduce spikes and wells, fill voids through interpolation, (large voids were left in the data) set the ocean to elevation of 0, flatten lakes of 600 m in length, steep down in height rivers with more than 183 m in width. Islands were depicted if with axis exceeding 300 m. This NGA product is referred as DTED Level 2 data. DTED level 2 was aggregated to 3 arc-seconds by assigning the value of the centre pixel to the corresponding 3 x 3 kernel of the 1 arc second data and referred to DTED Level 1. DTED Level 1 data thus differ from the NASA SRTM 2.1 that was aggregated by averaging.
- NGA data processing generated also a a shoreline water body data (SVBD). It was obtained through an analysis of the SRTM mosaics and the visual editing of Landsat imagery over the span of several years, as well as the use of medium scale maps (Farr et al., 2007).
- NGA post processing that resulted in the DTED Level 2 (1 arc sec) injected a set of shoreline pixel to 1 m "to contain water" (Farr et al., 2007) and at the moment of writing was also released as open source.

SRTM accuracy

- The original specifications for the production of the SRTM-DTEM aimed at obtaining a 16 m absolute vertical error, 10 m relative vertical error and 10 m horizontal error (Slater et al., 2006b). It is reported that the dataset "meets and exceeds the 16m (90%) performance goal, often by a factor of 2" (Rodriguez et al., 2006). Additional validation analysis identifies reported the linear vertical relative height error and circular relative geo-location error estimated of being less than 10.0m and 16.0m respectively for 90% of the data (Rodriguez et al., 2006). More elaborate details and reviews of SRTM datasets addressed accuracy and errors for specific applications (Rodríguez et al., 2006), (Gorokhovich and Voustianiouk, 2006), (Slater et al., 2006a), Farr et al. (2007), Jarvis et al. (2008) and Kervyn et al. (2008). Shortridge and Messina (2011) reported also on error in the spatial accuracy of SRTM over the USA. The work was not extended globally.

SRTM for use in this analysis

- This research uses SRTM Version 4.1 that stems from the NASA 2.1 processed to fill voids within CGIAR-CSI[i] (Merryman Boncori, 2016). In fact, as the NASA-SRTM 2.1 contains region of no data over large water bodies as well as in the region where the radar shadow effect is pronounced such as the Himalayas. Void were addressed by void fillings techniques (Reuter et al., 2007) and the resulting datasets is now used widely within the Hydrological community. Merryman Boncori, (2016) provides the results of the comparison between NASA-SRTM 2.1 and CGIAR-CSI SRTM v.4.1
- It is our understanding that the in CGIAR-CIS SRTM v.4.1 the oceans were masked using the SWBD providing a no data value, that facilitates the location of land below and above sea level.

We decided to use this CGIAR-CSI SRTM V.4.1 arc sec for the following reasons: (i) the source and method of production of the data is relatively well documented; (ii) there are some information on accuracy of the original dataset; (iii) the CGIAR-CSI SRTM V.4.1 dataset is the result of an incremental test/improvement procedure over the original release and it is documented; (iv) the coverage is complete between 60N-50S, (v) the spatial resolution is the closest to GHSL production resolution (i.e. 38m) among the available global DEM products that have been evaluated. Alternative open source products included the Multi-Error-Removed Improved-terrain DEM (MERIT DEM)[2] (Yamazaki et al., 2017) that upon visual inspections was deemed not suitable due to the very approximate shoreline delineation from which this paper so heavily depends on. In addition, we prefer to use one dataset rather than a combination of the two that are generated with different imaging technologies.

The GHSL suite used in this work includes built-up area (GHS-BU), population (GHS-POP) and settlement model (GHS-SMOD) grids (Figure 2). Four GHS-BU data layers describe the globe in four epochs, circa 1975, 1990, 2000 and 2014. The GHS-BU grids were derived from Landsat imagery (Pesaresi et al., 2016a) ([1] in Figure 2), and are available as classification grid (built-up/not built-up) at 38 m spatial resolution. GHS-BU is also available in aggregated form at 250 m and 1 km ([2] in Figure 2). The GHS-BU data have been combined with population census information to derive fine scale disaggregated population density layers. The information has been modelled at 250m grid that provided a continuous value of population densities ([3] in Figure 2). This procedure is fully described in Freire et al., 2015. Finally, the GHS-BU and GHS-POP grids are combined into GHS-SMOD grids ([4] in Figure 2). The applied settlement model is based on the settlement definition proposed by Dijkstra and Poleman, 2014, by its adoption at 1 km grid. In general, it relies on a set of thresholds on population densities (per cell) and total counts (per identified settlement), which are used to classify the global land mass ([1] in Figure 2) into high density clusters (GHSL-HDC) and low density clusters (GHSL-LDC) as described in Pesaresi et al., 2016b. In this work, only the HDC 2015 grid has been exploited.

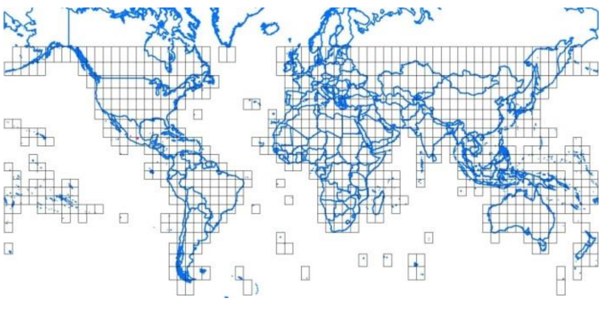

Figure 1. SRTM tiles and global coverage

[2] http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/

3 Methods

The procedure to quantify settlements in low coastal areas and steep terrain uses SRTM 3 arc sec to derive two categorical variables: elevation and slope. Four elevation classes were produced by setting a hard threshold on the available SRTM dataset. For the slope classes we first computed the slope – a continuous variable - from the SRTM dataset, then we threshold the slope variable into 3 slope classes (Table 1). The threshold for the elevation and the slope were derived based on the following points.

3.1 Defining elevation and slope classes

Each categorical slope class identifies areas where gravity exerts different degree of influence on both physical processes (i.e. harmful effect of hazardous natural process such as flash floods, landslides at different degrees) and societal processes (i.e. construction of road infrastructure, and built in general). The class threshold with slope below 5 degree (SL_1) identifies nearly flat terrain, where gravity exerts the least pressure and topography is not an impediment to regular settlements deployment. In slopes between 5 and 15 degrees (Sl_2) topography starts to become a significant factor in determining the settlement spatial patterns, moreover in these areas gravity becomes an important factor in modulating natural hazard severity. In class, Sl_3, (slope degree greater than 15°) slope is considered a limiting factor in establishing settlements and at that slopes gravity may be considered an important driver of hazards and disaster risk. The slope calculation is being grouped in classes where the highest class has most relevance for this research. Beyond 15 degrees settlements are rare, typically ignored by most global investigation, yet, to be found throughout continents.

LECZ were defined as coastal areas with elevation lower than 10 m in coastal area hydrological connected to the oceans (Mcgranahan et al., 2007; Small and Nicholls, 2003b). This research follows that initial definition and in addition we further split the LECZ in 3 classes. Coastal areas below sea level (El_1), between 0 and 3 m (El_2); and between 3-10m (El_3). The fourth class includes the region above 10 m in elevation (El_4) that is outside the scope of the definition of LECZ (Table 1).

Table 1. Thresholds used for categorizing elevation and slope classes

Elevation classes	**El_1**	**El_2**	**El_3**	**El_4**
Elevation range (meters)	El < 0	0 <El<3	3<El<10	El>10
Slope Classes	**Sl_1**	**Sl_2**	**Sl_3**	
Slope range (degree)	0 <Sl<5	5<Sl<15	Sl>15	

El_1 areas are either the coastal lagoons or areas protected by coastal infrastructure (engineering civil works) most vulnerable to change in sea level and to coastal hazardous processes. Below sea level has not been mapped globally before.

Class El_2 and El_3 was designed to outline the territory affected by coastal processes; including storm surge, potentially devastating tsunamis and all coastal processes including contamination of aquifer, soil salinization as well as centennial (Levermann et al., 2013) or millennial human induced seal level rise (Strauss et al., 2015)

El_2 was also devised to include errors in SRTM datum that may range in the order of 3-5 meters in height as estimated by the authors. In fact, the 10 m relative vertical errors and 10 m horizontal error reported for the original 1 arc sec may be reduced when aggregating - by averaging - to the 3 arc sec spatial grid used herein. El_2 class also aims to take into account the land that includes buildings 1 story high - typical of rural landscape in coastal areas – that are classed on higher ground only due to the inclusion of the building height in the elevation measurement. Similarly, forested landscape may also be included in higher ground class due to the inclusion of the canopy height in the elevation measure. In short, class El_2 may be considered the margin of error for class El_1, that assumption needs to be properly checked against reference data.

El_3 aimed to include that part of the territory that acts as an interface between the higher elevated areas, and that experiences, even to a lesser degree, the natural and human induced processes of the former two classes, El1 and El_2. The class El_4 includes land area 10 meters above sea level, which is the one less affected by coastal processes.

The thresholds for the slope classes were defined based on authors understanding of settlement pattern distribution in flat and rugged terrain. For what refers to the steepest class (SL_3) we inspected mountainous areas test sites in the mountainous and rugged terrain coastal areas. Mountainous test sites where: i) the Alpine region, with focus on settlements in Western and Eastern Alps (Julian Alps in particular); ii) the Himalayas focusing on settlements in the Annapurna south slopes range; iii) the Andes in Cordillera de Huayuash (Peru). We also analysed disaster reports related to flash floods in coastal areas with rugged terrain centred on Genova (Italy) and Cote D'Azur (France) and on informal settlements in steep terrain (i.e. Lima Rio de Janeiro).

3.2 SRTM data processing

SRTM data processing included a number of steps listed below and graphically illustrated in figure 2.

— Calculation of the slope grid from the elevation grid ([7] in Figure 2); In order to make the data suitable for slope calculation in metrics, first the SRTM grid was projected from the geographic coordinates (WGS84) into the Universal Transverse Mercator (UTM) coordinate reference system (cubic resampling). The slope was calculated using GDAL tool 'gdem', which is dedicated to analyse and visualize DEMs. This tool implements the slope algorithm using Horn's formula which performs better on rougher terrain (Horn, 1981). Per each cell the slope degree is derived from an integrated 9 cell (i.e., via a kernel size of 3 x3). The slope output raster map contains slope values, stated in degrees of inclination from the horizontal plane. Due to the fact that the algorithm used to determine slope uses a 3x3 neighbourhood for each cell of the elevation grid, it is not possible to determine slope for the cells adjacent to the edges in the elevation map layer. This effect was mitigated by overlapping processed area.

— Re-projecting the elevation and slope grid cells in Mollewide projection, aggregating the values at 250x250m spatial grids, and recoding the two variables into classes based on thresholds as from table 1 ([6],[8] in Figure 2);

— Calculating per each class of elevation and slope the amount of built-up area and population ([9], [10], [11] in Figure 2). For each GHS_BU dataset (one for each epoch), four intersection operation are carried out one for each of the four elevation classes. That is referred as GHS_BU_75_el{1,2, 3,4}, to GHS_BU_14_el{1,2,3,4} for a total of 16 intersection (step [9] in figure 1). The values derived are to be used for analysis using any spatial unit as area of aggregation. This study shows the country and the settlements outline (for steep terrain) as the spatial unit of aggregation. The operations will return statistics in table format that quantify the amount of built up for each epoch in the four elevation classes for the countries of the world within the spatial extent of the SRTM datasets.

— Similarly to GHS_BU, the GHS_POP is combined with the elevation classes to obtain a GHS_POP_El _that is also_a continuous vale (step [11] in figure 2).

— Finally, the GHS_BU_El, and GHS-POP_El and GHS_BU_Sl and GHS_POP_Sl are crossed with the spatial units defined by the GHSL HDC and GHS-LDC.

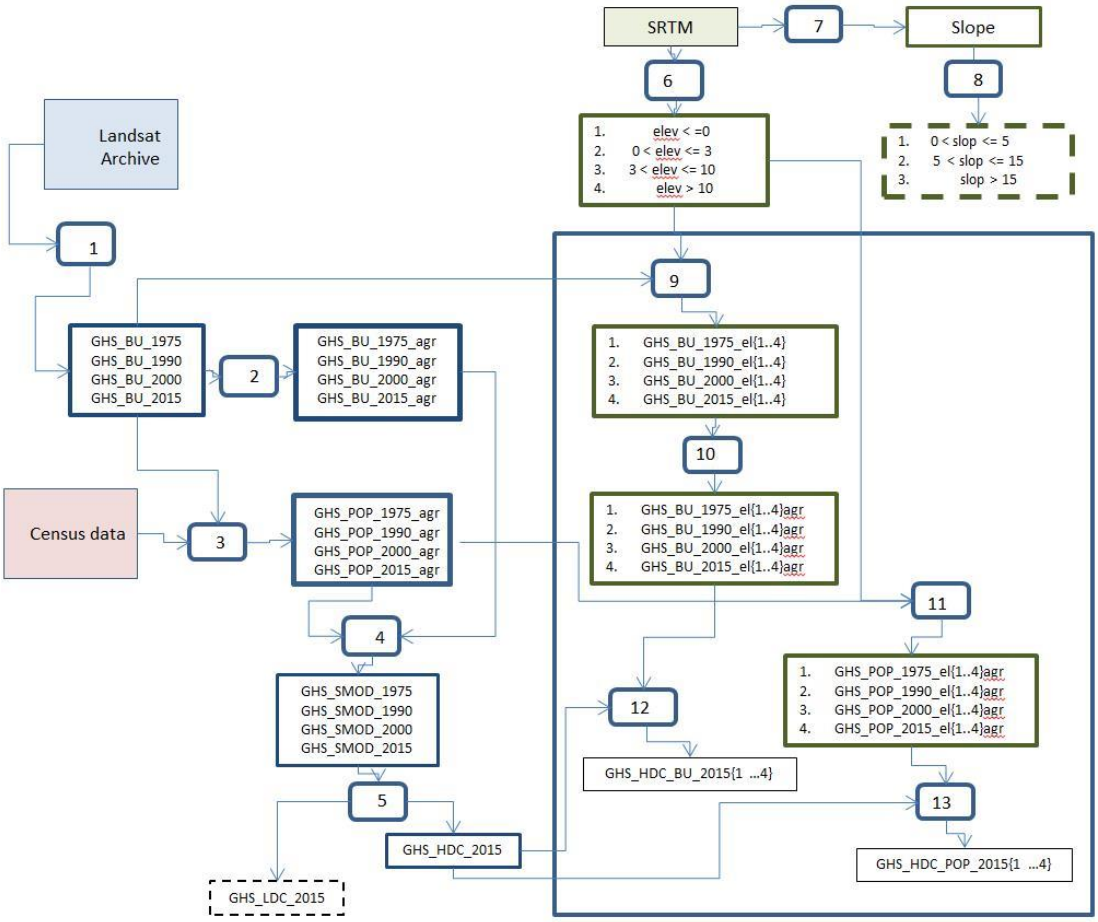

Figure 2. **Overview of the processing workflow; the blue boxes identify the datasets being part of the GHSL data package, while the green boxes identify the datasets produced for the purpose of this analysis. The blue-shaded box defines the satellite data and the pink-shaded box identifies census data, both used in the production of the main components of the GHSL data set.**

4 Results

SRTM 3 arc sec (CGIAR-CSI SRTM V.4.1) analysis reveals that low elevated coastal zones are to be found in all continents. The low elevation coastal areas fall in three geomorphological categories: the large river deltas, the naturally low lying coastal areas, and the low elevated small island states (Fig. 3). A number of low elevated areas are also not hydrologically connected and to be excluded from future analysis of LECZ. All are influenced by geomorphological process in equilibrium over longer time scales.

Elevation data at the spatial resolution available from SRTM can be used to report statistics at local, regional and national geographical scale with the limitation that the dataset and thus the analysis stops at 60 degrees latitude North. Slope statistics can be used as proxy indicator for aggravating factor of natural hazards impact. Slope statistics reporting over regions or country are relevant for infrastructure planning and accessibility also for crisis management applications. The national statistics are calculated based on the Global Administrative Areas (GADM)[3] open source dataset.

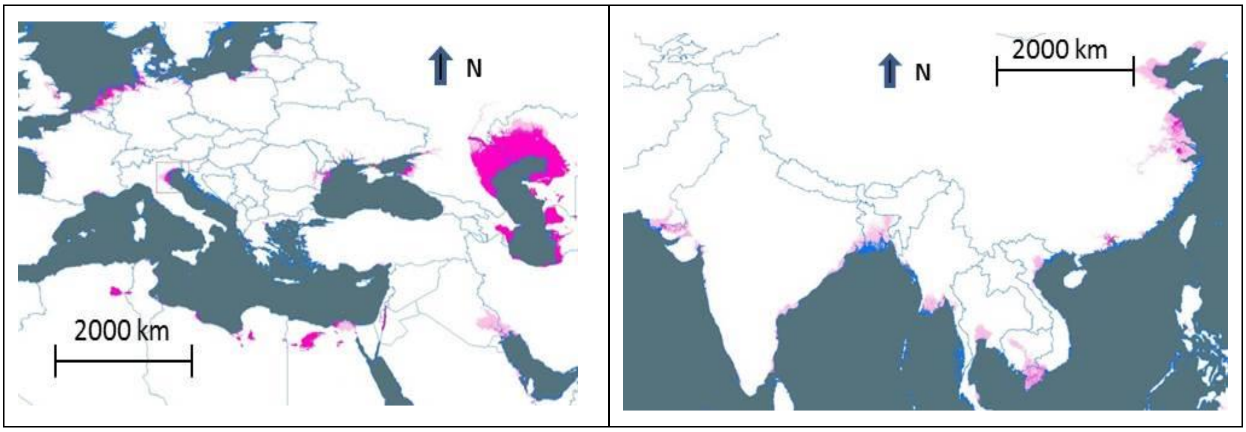

Figure 3. Examples of low elevated coastal areas in Europe (left) and in Asia (right)

4.1 Settlements in low elevated coastal zones

This report cannot produce national statistics for countries whose territory is outside the coverage of SRTM data, namely Russia federation USA and Canada, Norway, Greenland, Iceland, Sweden and Finland. However, we provide statistics on total population living in areas below sea level (Figure 4) within the geographical extent of SRTM. Also, we show national statistics for selected countries. For example figure 7 shows that China is the country with the highest population in LECZ below sea level if we consider that Russia, Canada and the United States have been excluded from the analysis. The Netherlands in this preliminary is the second country with the highest population in LECZ below sea level (Figure 5). The relative population increase in LECZ between 1975 and 2014 has more than doubled in most countries including Egypt, Iran, and Vietnam (Figure 5).

[3] http://www.gadm.org/

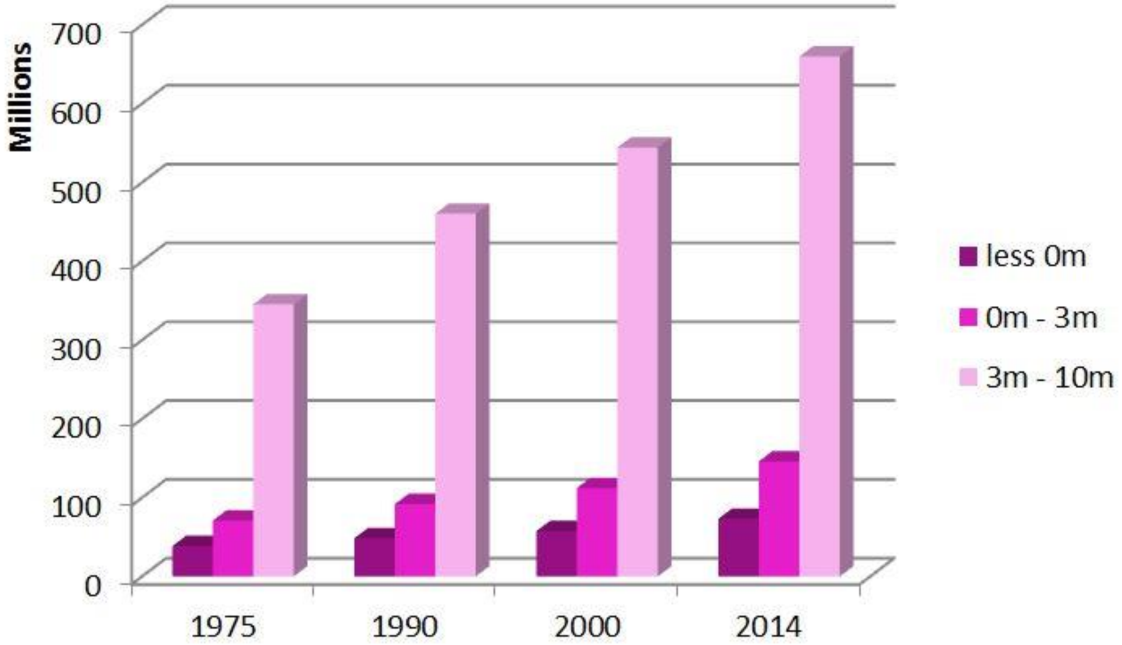

Figure 4. Global population in Low Elevated Coastal areas in four epochs for land masses between Latitude 45 degrees S and 60 degrees N.

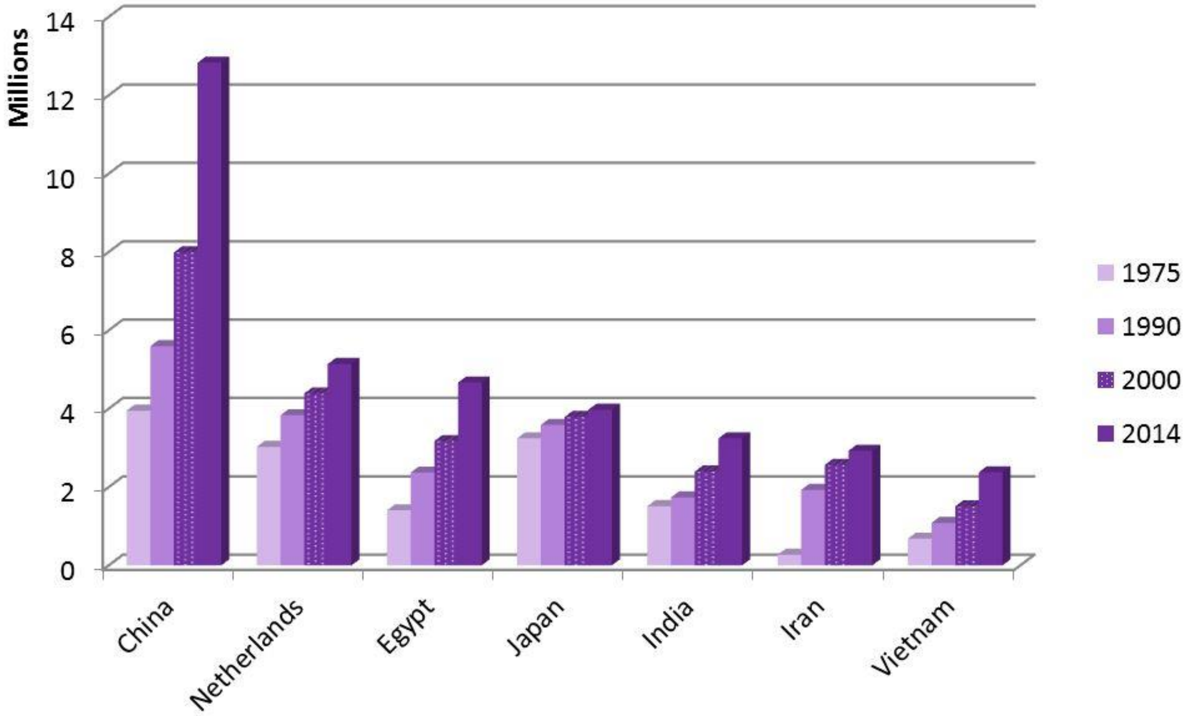

Figure 5. Eight countries with high population in Coastal Zones below sea level

4.2 Settlements in LECZ measured at national level

This section provides examples of national LECZ statistics generated from datasets processed in this work. Figure 6 shows the map of LECZ computed from SRTM 3 arc sec as well as GHS-BU for The Netherlands. Figure 7 shows the intersection of the same LECZ and built-up map and the population statistics derived from the four epochs and the four elevation classes. The Netherlands (figure 7) shows highest percentage of population in LECZ over the total population of the country (Annex 1). Based on this early analysis, in 2015, more people live in areas lower than sea level (in ginger pink in Figure 7 left) than those living in high elevated areas when (Figure 7 left in light pink). The statistics show that the number has increased from nearly 3 million people in 1975 to over 5 million in 2015. These statistics will have to be compared with the statistics generated by the countries using more precise instruments. The aim here is not to provide a final figure of population or built up in a given geographical area of the world but rather to show the process by which we can derive these measures based on the dataset we are using. Future comparison and validation will have to take into account the semantic with which the elevation classes are defined, as well as the precision and the scale of the data collection protocol that all will influence the outcome.

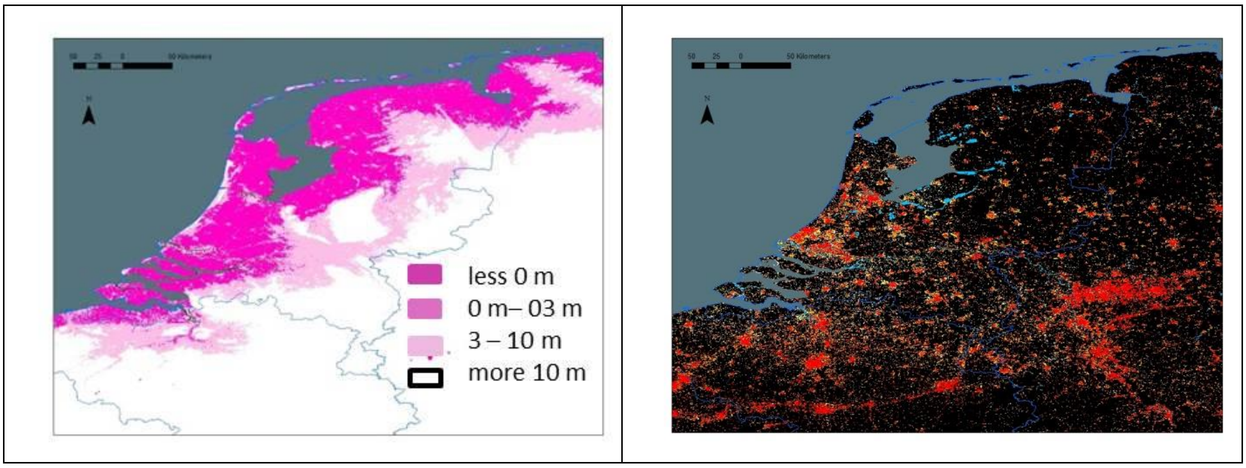

Figure 6. LECZ centred on The Netherlands as computed from SRTM (left) and GHS-BU for the same area (right).

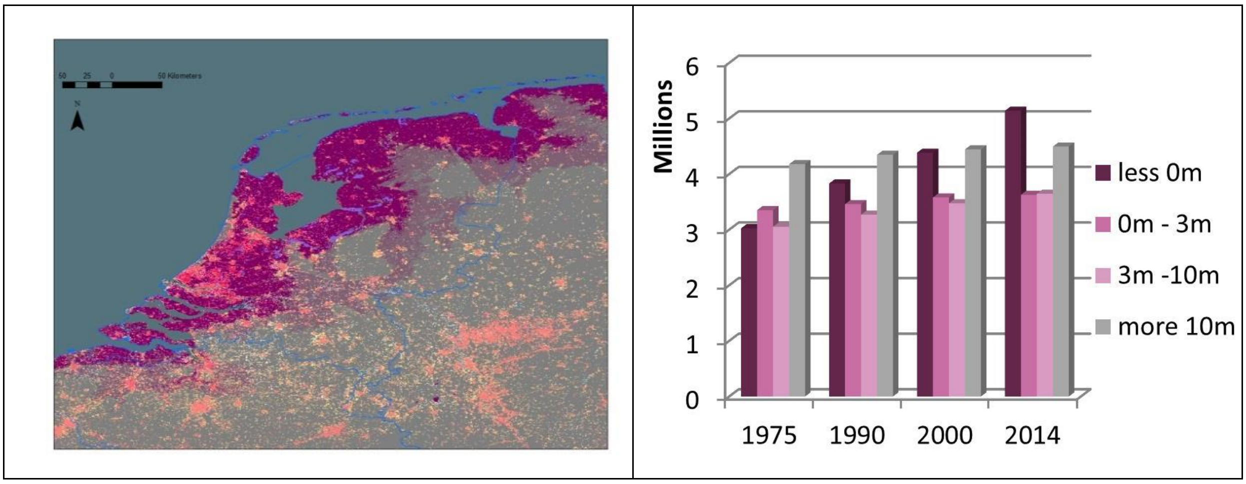

Figure 7. Overlay of LECZ and GHS-BU for The Netherlands (left) and population figures aggregated for The Netherlands in four elevation classes for the four epochs (right) .

The extraction of statistics on population and built up in the different elevation zones and for the different epochs can be obtained for any country of the world and any geographical areas. Figure 8 shows examples of statistics for Vietnam (Annex 2) that relatively to its population has the second highest percentage of population in LECZ. Figure 8 b shows the statistics for Kiribati (Annex 3) that show that Small Island Developing States are particularly vulnerable to sea level rise and associated hydrological and meteorological hazard because have both the relative and total population in LECZ.

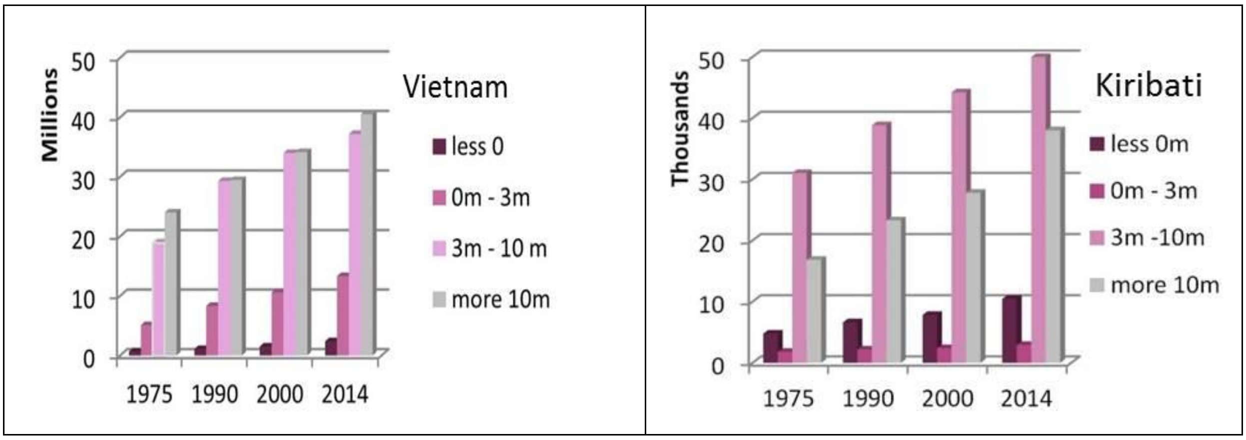

Figure 8. Elevation classes figures for Vietnam (left) and Kiribati (right)

4.3 Slope analysis

Relief is a major determinant of settlements spatial distribution. Population living in settlement in steep terrains are typically vulnerable to gravity related hazards. In fact, people prefer to build in flat and accessible terrain as steep terrain can be associated with landslides flash flood and a general more unstable landscape setting on which to secure buildings and households. Steep terrain can be found in historical cities in mountainous areas. However, a number of cities not associated with mountains may also show geographical settings with steep terrains (i.e. Rio de Janeiro, Brazil; Genova, Italy) that may experience the impact of hazards such as landslides and flash floods.

4.3.1 Slope analysis

National statistics on slopes are used also assess the accessibility of settlements. Accessibility is an important economic development parameter. However, it is the statistics calculated at the local level that provides insights on the potential hazard that may originate in that settlement. The national statistics on slopes and the local statistics on slopes are illustrated below.

Figure 9 shows national slope statistics calculated by aggregating the data available at the grid level. That assumes that spatial grids of population are available for the countries for the four epochs addressed in the study. This analysis did not have at disposal a complete and consistent spatial grid of population for all countries for all four epochs. In addition, the graphics and statistics are preliminary as validation will be required. Figure 9 provides an example of total population in relief terrain with more than 15 degree slope for a selected number of countries excluding Russia Federation, USA and Canada.

The statistics reflect the topography of the country as well as its size with China ranking highest due to its size and complex relief. The statistics also reflect some anomalies in the datasets. For example we were not able to provide the 1975 population aggregates for China. Also, the datasets on steep terrain for Nepal are also not available for the epochs ranging from 1975 to 2000. The figures need to be re-evaluated as the new improved data will be available with finer scale datasets.

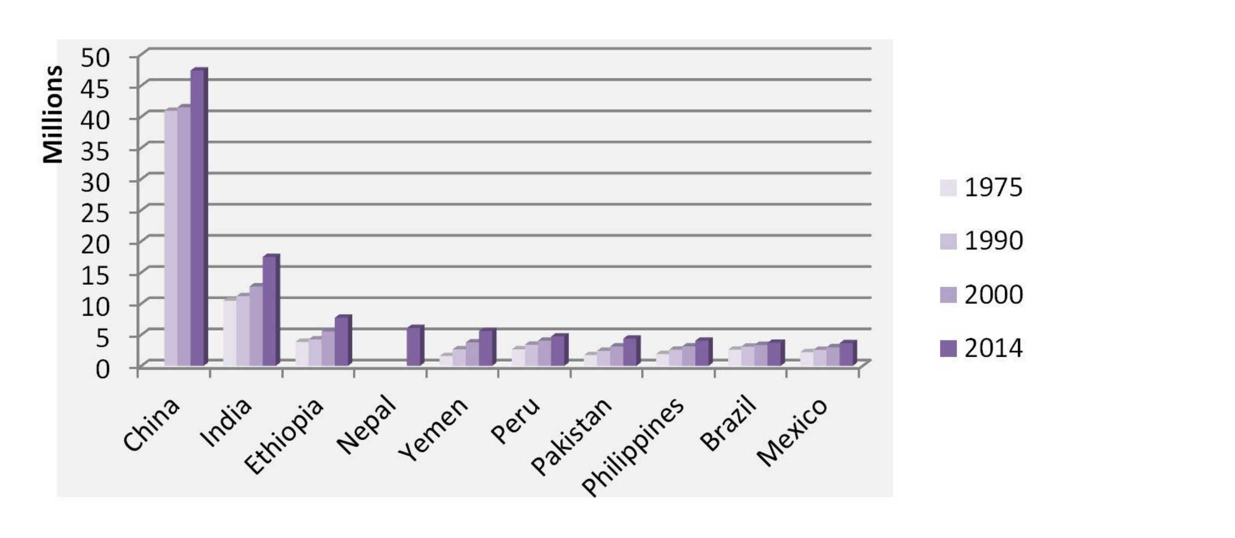

Figure 9. The ten highest ranking countries for population in terrain steeper than 15 degrees (excluding countries above 60 degrees North)

4.3.2 City level slope statistics

The value of the slope classes calculated from the SRTM is based at local scale at the city level. The city outline is calculated using the two GHSL layers, built-up and population density resampled at 250 x 250 m grid size. The outline in figure 10 is based on the High Density Clusters calculated at 1 x 1 km grid size. The statistics show that the population has increased and more than doubled since the 1975. Population has increased mostly in the flat areas and to smaller extent also in steep slopes.

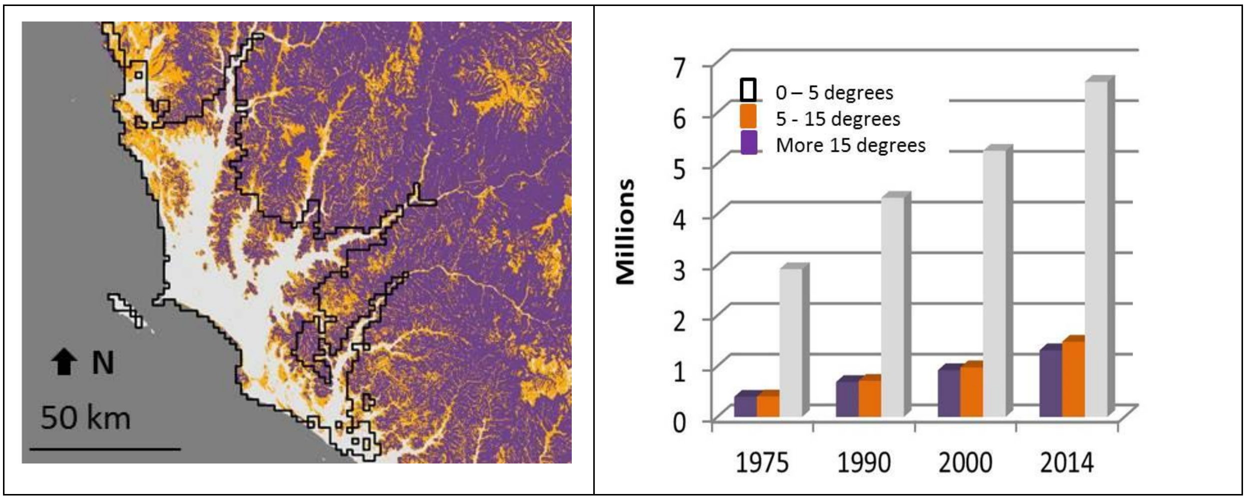

Figure 10 Outline of the High Density Cluster of the city of Lima (black outline) with the three slope classes: less than 5 degrees (grey) , between 5 and 15 degrees (light brown), and above 15 degrees (violet).

5 Results and discussion

The datasets and analysis reported herein provides an improved insight in distribution of people in low coastal areas and steep terrain. The datasets used, SRTM and GHS , are one order of magnitude better than those used in previous analysis (i.e. Mcgranahan et al., 2007). For examples, there is large improvement when compared to slopes computed from the 30 arc dataset that smooth out many of topographic features of interest for human habitation. Also, the 30 arc sec datasets underrepresents coastal land below sea level with few exceptions that include the Netherlands. The GHSL layers map settlements at the resolution at which the settlements occurs. As the data are variable in gridded format and standardized n space and time the data can be aggregated to the spatial unit of required for reporting. The data allows to describing processes at the scale at which they occur that often is a local scale.

Major challenges remain. The main shortcomings are related to the SRTM datasets and the additional processing used to correcting the datum.

SRTM shortcomings and challenges for the next generation of DEM

- There is no ultimate error figure associated on the spatial distribution of the errors that is sufficient for the scope of this analysis.
- The vertical 10 m spatial error and 10 m vertical error (Rodriguez et al., 2006) reported for the original 1 arc sec may in part be mitigated through the aggregation to 3 arc sec. However, that also requires verification.
- More detailed studies may be needed to understand the error in elevation associated to the different land covers, especially on the low elevation coastal areas where few meters may make a different in attributing a part of the land to one or the other elevation class.
- The accuracy measured on the original SRTM 1 arc sec is not supportive for elevation analysis more refined than what attempted herein. In fact, the class 0m to 3 m may be considered also as the error range for class below sea level class.
- The SRTM datasets assumes oceans as flat surfaces with sea level (0 m) that in fact were artificially recoded to produce the SRTM 3 arc sec. This first order approximation may be sufficient for selected applications but not for calculating potential coastal inundation. We feel that the "local sea level" rather than the "global seal level" should be available in order to measure the relative sea level trends using dedicated instruments as addressed in Strauss et al., (2015).
- Coastal outline. The coastal outline we have used is the result of manual editing that may need to be replaced by a more consistent procedure that may take into account daily variations (i.e. tides) as well as a longer term sea level changes.
- Follow up research should consider using the SRTM 1 arc sec produced by NGA and evaluate the post processing included as it is different from that embedded in the CIGAR-CSI SRTM 4.1.The finer spatial scale and more precise SRTM 1 arc sec could help to better separate the constructed environment from the actual elevation on which settlements are built. The next generation DEM should allow to separating building and vegetation height from that of the ground. We understand however, that the vertical absolute and relative error will remain one of the most severe obstacles (Simpson et al., 2015), .
- For LECZ only finer resolution and higher precision elevation, as tested by that of SRTM Griffin et al., (2015), can provide the appropriate modelling on costal inundation required for crisis management (Simpson et al., 2015).
- The slope calculations implemented on SRTM (CGIAR-CSI SRTM V.4.1) include cells of approximately 90x90 m. The slope is computed over an area of 270 x 270m that averages out changes in elevation spatially smaller than one hectare.

Finer spatial grids (i.e. SRTM 1 arc sec) may in part mitigate the averaging factor and account for quarter of one hectare.

- Incomplete coverage for high latitudes should be addressed. At this moment Canada and Russia as well the United States with Alaska are underrepresented for the lack of data beyond 60 degrees north. If SRTM is to be used then the areas North of 60 degree latitude should be clipped out from the national statistics and slope and elevation figures should be re-evaluated accordingly.

GHSL improvements

- Verification of GHS layers; the first release of Landsat based GHSL is one order of magnitude better than datasets on settlements available to date and the future validation will provide an additional quality mark on the datasets.
- Current omission and commission errors will be reduced with the new available processing of Sentinel data and in the future of even finer resolution data.

Future improvement in the procedure

The low elevation zones computed in this research include that of inland waters such as the Caspian Sea. If the purpose is to analyse sea level rise then these areas need to be separated from the LECZ in the proximity of the oceans as they are exposed to similar hazard i.e. flooding, that however originated from other cause. The improvement of this work will include the classification of LECZ below sea level.

6 Conclusions

This SRTM datum at 3 arc sec improves our ability to study human settlements in low elevated coastal areas and in rugged terrain globally below 60 degrees north. For what concerns coastal area we build upon research conducted with data one order of magnitude coarser – 30 arc sec - DEM data (Lichter et al., 2011). We show that the SRTM at 3 arc sec can be recoded in three meaningful LECZ elevation classes of which one captures land below sea level. We show that we can aggregate human settlement statistics on the three LECZ for any geographical area. From this preliminary analysis we feel that the four elevation classes we have identified are appropriate for addressing areas potentially exposed to coastal hazardous processes. The slope classes are equally well suited to address topography as a determinant of spatial distribution of human settlements as well as aggravating factor in gravity related hazards. In future analysis, we may wish to include a fourth slope class for terrain steeper than 20 degrees especially if we would be able to process datasets at finer spatial resolution and with higher vertical and horizontal precision.

The biggest limitation of this procedure resides in the accuracy of the input data and in the accuracy measures that come with the data. We confirm that SRTM data is deemed not suitable for precise local studies that are required for crisis management and disaster risk assessment. In fact, no open global elevation datasets is available to date to support local and regional analysis on LECZ. We support the appeal for a global finer spatial resolution DEM with higher vertical and horizontal accuracy for use, among many applications, also to support operational crisis management procedures and more realistic disaster risk assessments.

Despite these shortcomings, the data layers produced in this research are suitable for a global quantification of Low Elevated Coastal Areas and rugged terrain especially for spatial and temporal comparison of built-up and population. The value of the exercise resides specifically in multi-temporal GHS layers that span from 1975 to the present and allow for an assessment of exposure to coastal hazards over time. This preliminary data exploration and procedure testing shows that we may be able to significantly improve our understanding of relief as a determinant of settlements spatial patterns and the pressure of human activity on vulnerable geographical settings.

We found this type of research useful for addressing global analysis of coastal areas that is particularly sensitive to geomorphological processes including erosion, subsidence, changes in sea level and susceptible to impact of hydro-meteorological hazards including sea level surge and tsunami and will have to be monitored over time. In fact, some of the process may be amplified by human processes including land cover and use change, deforestation especially of the mangrove forest in tropical coastal zones. These processes need to be better understood in order to prevent to trigger unsustainable processes that will generate future risks to human societies. The understanding starts with measuring human presence and the GHS layers are among the most relevant as they quantify both the impact on natural processes and serve also as the exposure, what is most valuable to societies, to the impact of natural hazardous processes. That understanding can be strengthened through repeated measurement of settlements, the most important variable in risk analysis that will ultimately provide data to build indicators and trajectories of future development used by policy makers to address sustainability.

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Annexes

Annex 1. Population per Epoch in the Netherlands per Elevation Class

Elevation in metres	1975	1990	2000	2015
<0	3,026,190	3,830,737	4,384,398	5,139,082
0<El<3	3,352,311	3,460,429	3,580,536	3,627,726
3<El<10	3,052,188	3,269,278	3,474,567	3,646,398
>10	4,179,099	4,347,308	4,444,465	4,495,614

Annex 2. Population per Epoch in Vietnam per Elevation Class

Elevation in meters	1975	1990	2000	2014
<0	682,096	1,083,031	1,505,373	2,376,834
0<and<3	5,094,416	8,323,085	10,589,136	13,327,427
3<and<10	18,920,417	29,317,682	34,005,985	37,205,043
>10	24,028,011	29,475,319	34,170,727	40,499,754

Annex 3. Population per Epoch in Kiribati per Elevation Class

Elevation in metres	1975	1990	2000	2014
<0	4773.541	6621.589	7833.966	10468.28
0<and<3	1794.72	2183.978	2406.491	2924.232
3<and<10	31038.31	38851.33	44216.31	57353.03
>10	16848.93	23295.85	27797.48	38021.96

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