THE DISTRIBUTION OF PEOPLE AND THE DIMENSION OF PLACE: METHODOLOGIES TO IMPROVE THE GLOBAL ESTIMATION OF URBAN EXTENTS

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ABSTRACT:

What is known about the urban world is largely derived from local knowledge. This paper showcases substantial efforts at new data integration with existing technologies to develop a new suite of global datasets on urban population and extents. These new databases far surpass past efforts to construct a systematic global database of urban areas by combining census and satellite data and methods of analysis in an integrated geospatial framework. The resulting data allow for inquiry into analysis of urban issues and population by environmental and other ecological characteristics in novel ways. This paper focuses on the methodologies employed to construct these new datasets. Summary results regarding population distribution at continent- and global-levels are also given, as well as suggestions for future research.

1. INTRODUCTION

1.0 Introduction

Human settlements occupy a relatively small fraction of Earth's surface area but their extent and distribution have significant impacts on their surroundings, both from an environmental and a socio-economic perspective. By 2007, it is estimated that over half of the world's population will reside in urban areas (United Nations, 2002a). Despite increasing knowledge about the characteristics of urbanization, little is known about its spatial dimensions. For example, only guesswork has provided prior estimates on the share of the world's inhabited land area that is urbanized, or on the classification of the world's population by city-sizes other than the very largest ones (UN, 2002a; UN, 2002b). Even when cities are tallied by their population sizes and types (such as agglomerations), little effort has gone into systematically capturing the spatial dimension of these places.

In order to understand and study the impacts of urbanization, population and physical factors need to be made available as detailed, spatially disaggregated data and reduced to comparable scales. Although there is ample research on urban growth as separate geographic and demographic phenomenon, there is little research and no dataset in which these parameters are integrated. This study proposes a new methodology to foster this integration. That methodology is the focus of this paper, along with the discussion of some analytical results and suggestions for future research.

2.0 Background

While many environmental data are available already as spatial datasets, demographic data tend to be collected by administrative units and therefore require some form of spatial allocation to convert irregularly-shaped census units to globally or regionally consistent population grids. Several researchers and institutions in recent years have used new methods and data to map the global distribution of human population. The first major effort to generate a consistent global georeferenced population dataset was the Gridded Population of the World (GPW) (Balk and Yetman, 2004), produced at the National Center for Geographic Information Analysis (NCGIA) in 1995 (Tobler *et al.*, 1997), and updated by CIESIN in 2000 (Deichmann *et al.*, 2001). The inputs to the GPW dataset are solely administrative boundary data and population estimates associated with those administrative units. Other efforts then followed, generally incorporating satellite data and other ancillary data which reallocate population towards classifiable features such as roads (UNEP, 1996a, 1996b, 2000, 2004, and CIAT, 2003) and slope, elevation, night-time lights, and land cover (Dobson *et al.*, 2000). Each of these approaches has strengths and weaknesses. The study presented here forwards a new methodology drawing on the heuristic approach, but it also attempts to improve output resolution by accounting explicitly for urban areas.

In the process of reallocating population to urban areas, it is necessary to first construct a spatial database of those areas. To accomplish that, satellite data were a necessary additional input. The Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) "night-time lights" dataset has been increasingly used to estimate aspects of human activity at the global level, and thus was again used in our project (Elvidge *et al.*, 1997). Other recent efforts include a pilot study to map urban land cover by fusing the night-time lights dataset with GPW and a MODIS-derived land cover classification (Schneider *et al.* 2003), and Pozzi *et al.* (2003), which maps global urban population by integrating GPW and the night-time lights. None of these efforts, however, attempts to merge the lights directly with city-level census data to derive population estimates of urban areas. Thus, using GPW as a base, in 2000, CIESIN, IFPRI, the World Bank and CIAT

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began the multi-year effort of the Global Rural Urban Mapping Project (GRUMP). This effort aimed not only to construct an improved population grid, but also to construct a globally consistent database of urban areas.

The methods presented in this paper are based on the premise that data may be combined from several disparate data streams: census (or census-type) inputs on the population size (of settlements and administrative areas), with associated names; and two key pieces of geographic information, latitude and longitude of settlements, and boundaries for administrative areas and urban extents (the latter being identified using the night-time lights and ancillary geographic datasets). The resulting dataset consists of three distinct products: a human settlements database, an urban extent database, and an urban-rural population grid or surface.

2. METHODOLOGY

These new methodologies result in three new databases: 1) a Human Settlements database, 2) an Urban Extent database or mask and 3) an Urban-Rural population grid or surface (CIESIN *et al.*, 2004a, 2004b, 2004c). Here we briefly describe the methodology—and underlying data—used in the development of these datasets (cf., Balk *et al.*, 2004 for details.)

1.0 Human Settlements

Although there are many gazetteers listing populated places, few of these contain population estimates for those named places. Similarly, databases of city population estimates rarely include geographic information, such as the latitude and longitude coordinates let alone area or other spatial information about each urban area. Several collections, such as the UN *Demographic Yearbook* (UN, 2002b) or the UN's *World Urbanization Prospects* (UN 2002a) include coordinates, and type of urban area, for places of 100,000 and 750,000 persons, respectively.

The GRUMP human settlements database is a global database of cities and towns of 1,000 persons or more, where each settlement is spatially represented as a point, and has associated tabular information on its population and data sources. Population data were gathered primarily from official statistical offices. Based on the data available and applying UN growth rates, we estimated population in 1990, 1995, and 2000. In some cases, the records for cities and town included latitude and longitude coordinates. For those where coordinates were not available we matched the settlement name and administrative units with the National Imagery and Mapping Agency (NIMA) database of populated places. Table 1 shows the distribution of data sources, while Figure 1 shows the settlement points database in a portion of South America, by population size.

Source	Asia	Africa	Europe	North America	South America	Oceania	World	Percentage
Census	9,666	2,525	6,641	27,493	4,889	451	51,665	73.2
World Gazetteer	2,210	561	4,799	243	74	168	8,055	11.4
CityPop	1,363	319	3,364	443	304	179	5,972	8.5
Others	7	737	0	119	4,002	1	4,866	6.9
Total	13,246	4,142	14,804	28,298	9,269	799	70,558	100.0

Table 1. Distribution of population data sources by continent

2.0 Urban Extents

While much research has been undertaken to describe the extents, landscapes, and changes of local urban areas, none has been undertaken in a systematic way at the global level. Efforts to use moderate-resolution vegetation-detecting optical satellite imagery prove too costly, and inconsistent, to detect built-up areas globally (Small, 2004, Tatem *et al.*, 2004). While other satellite data, such as new radar data from SRTM, holds promise for the detection of built-up areas globally, (Ngheim *et al.*, 2001), the effort has yet to be attempted.

The GRUMP Urban Extent Mask attempts to somewhat crudely represent the extents associated to the human settlements. In particular we now describe the sources of the physical extents of the settlements and the methodology to assign population from the point database to the areal extents. The physical extent of settlements has been derived both from raster and vector datasets, in particular:

- Night-time lights, produced using time series data from the DMSP-OLS for the period 1 October 1994 to 30 April 1995, where the pixel values are measurements of the frequency with which lights were observed, normalized by the total number of cloud-free observations. To delineate the physical extent of human settlements we used the World Stable Lights dataset ("cities" component).
- Digital Chart of the World (DCW)'s Populated Places: an ESRI product originally developed for the US Defense Mapping Agency (DMA) using DMA data and currently available at 1:1,000,000 scale (1993 version). The "populated places" coverage is available for most countries and contains depictions of the urbanized areas (built-up areas) of the world that are represented as polygons at 1:1,000,000 scale.
- Tactical Pilotage Charts (TPC): standard charts produced by the Australian Defense Imagery and Geospatial Organization, at a scale of 1:500,000, originally designed to provide an intermediate scale translation of cultural and terrain features for pilots/navigators flying at very low altitudes. Each chart contains information on cultural, drainage/hydrography, relief, distinctive vegetation, roads, sand ridges, power lines, and topographical features. Settlements are reported both as polygons and points. Polygons and points were digitized for a number of countries, especially where lights and DCW data did not adequately delimit urban areas.

All the sources of urban extent were combined in order to obtain the maximum possible coverage for each country. The night-time lights were used as a baseline (due to its global coverage), and then polygons that did not intersect any existing light were added from other sources. Therefore, the total number of urban polygons in each country is the number of lighted areas plus all the other polygons identifying settlements that were not already identified by the lights.

These polygons are characterized only by the basic geographic attributes, such as area and perimeter and do not have population attribute data. To create the Urban Mask from all the different sources we developed a hierarchical process, as follows.

First, we assign population from the points to the settlement extents, based on a 3km buffer distance (Elvidge *et al.*, 2004). If multiple points are present, as in the case of an urban agglomeration, the sum of the population of all points is assigned to the polygon. The name of the most populous city within the buffer is assigned to the polygon. Then, we estimate areal extents for points without polygons, based on a relationship between population size and areal extents for the points with known parameters. This relationship is derived from a logarithmic regression that predicts the expected geographic size of a place, given its population size. Where the number of observations is greater than 20 known relationships, we use country-specific regressions, otherwise regional regressions were used where regions were constructed according to the UN Statistics Division (UNSD) sub-continental regional codes. Based on these area values, we create circles, centered on the points. Finally, we add these newly created polygons to the existing ones to create a complete urban extent coverage for each country. Figure 1 shows the extent of urban places (as identified by the urban mask) in a portion of South America.

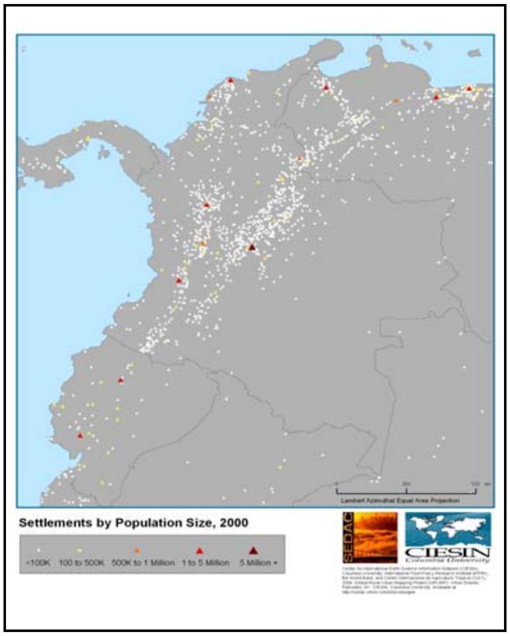

Figure 1. Settlement point database in a portion of South America, by settlement size.

There are two main problems that arise when using the night-time lights dataset as a baseline to identify urban extents: the insufficient detection of small settlements that are not frequently illuminated and the blooming effect. While the first problem has been reduced by using ancillary data, such as DCW and TPCs polygons, the blooming effect still remains unsolved. The blooming effect is an overestimation of the real extents of urban areas, and is believed to be dependant on the intrinsic characteristics of the sensor (Elvidge *et al.,* 2004).

3.0 Urban-Rural Grid

The Urban-Rural grid is a 30-arc second population distribution raster dataset that was developed by combining population data from the census administrative units and from the Urban mask. To create the urban-rural surface, we developed a mass-conserving algorithm called GRUMPe (Global Rural Urban Mapping Programme) that reallocates people into urban areas, within each administrative unit. In particular we used data inputs from two vector sources: (1) administrative polygons, containing the total population for each admin unit, and (2) urban areas, containing the urban population for each area. The algorithm works on a country-by-country basis and uses the following pieces of information: the size and population of each urban area, the size and population of each administrative area, the size of the intersect areas where the urban and administrative areas overlap, and the UN national estimates for the percentage of the population in urban and rural areas. The goal of the algorithm is to reallocate, or adjust, the total population in each administrative unit into rural and urban areas using information from the UN national rural/urban percentage estimates and those from the countries, as guidelines.

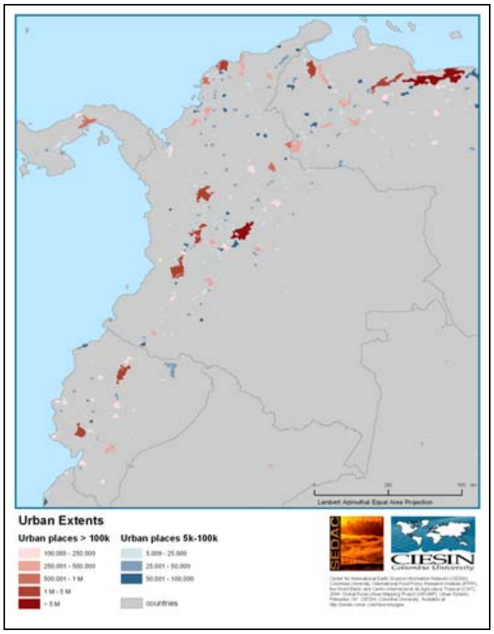

Figure 2. Urban extents in a portion of South America, by settlement size.

The adjustment in population is trivial when there are none or one urban area per administrative unit, and where the urban area lies wholly within the administrative unit. It becomes increasingly complex however when there are more than one urban area, and urban areas overlap more than one administrative area (e.g., Cali), and large urban areas contain more than one administrative area (e.g., Quito). All of these are common situations, and may require successive iterations to meet all the constraints. The algorithm can also be run on a region-by-region basis (such as states or other first-level administrative units), such that the national constraints (3 to 6) now become regional constraints and will better reflect the state-level variation in rural/urban population percentages in large countries like the USA. This approach was employed for most of the largest countries.

The resulting map is shown in Figure 2, with a close up of Cali, Colombia, showing the data before and after running GRUMPe. Note how, where urban areas are present in a given administrative unit, the density of the GPW administrative units decreases after GRUMPe because people are reallocated into their respective urban areas. The final results from each country are recorded in an excel spreadsheet to compare the output rural and urban population totals to the UN totals. Although the UN totals are useful as a benchmark, they are only that. Not only have recent studies shown the uncertainty associated with UN urban estimates (NRC, 2003), there are many reasons why our estimates may differ considerably from that of the UNs. For example, our data stream may have included many more small settlements, including those below the urban threshold either given by the country, or implied by the region, in which case we might the comparison between percentages of the population living in urban areas to be quite different between the two. The output coverage from GRUMPe is then converted to a grid, at 30 arc-seconds resolution.

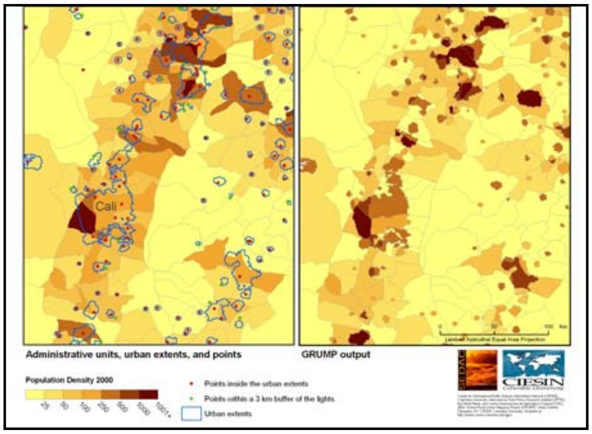

Figure 3. Population density of Cali, Columbia, and the surrounding areas. Original administrative units along with the urban extents and the point settlements (l) and reallocated results (r).

3. DISCUSSION

The methodology presented has some advantages and some disadvantages compared to existing datasets and methods. There are several shortcomings, including: a known "blooming effect"—an overestimation of the real extents of urban areas, and is believed to be dependant on the intrinsic characteristics of the sensor (Elvidge *et al.,* 2004)—of the urban areas, an inability to detect less-electrified regions of the world, and missing settlement points. The former leads to an overestimation of the size of some urban areas, and the latter two concerns leads to detection of fewer urban areas. Elsewhere, we discuss the implications of these shortcomings in detail (Balk *et al.*, 2004).

Though blooming is noted to be a problem, it is probably much less of one for the production of a global population distribution grid because that redistribution is to go from even much coarser administrative units to these urban areas. The direction of the reallocation we argue is a vast overall improvement in the database. Furthermore, for the largest cities, where blooming is probably greatest, there tend to be better sub-urban administrative units, so that the population within the extents will show the detail of the underlying detail. Nevertheless, future work should continue to determine the possibility of reducing the lights, as appropriate, so that the blooming effect is minimized.

This method has the advantage of *using* population data for settlements from census data, rather than *predicting* population density based on probability coefficients or lighted areas. Therefore we have an independent and reliable measure of population. Further, this methodology makes use of other GIS data to identify urban areas, compensating for the small settlements in poor countries that are not detected by the night-time lights. We know that the lights dataset has two main problems: the blooming effect and the insufficient detection of small settlements that are not frequently illuminated. While there is not yet a method to improve upon these two elements at a global scale, using ancillary data to identify small settlements has proved useful in several countries in Africa. Second, although this method produces a model surface, as opposed to a more heuristic one from GPW, it allows for improvements not only in resolution but also in the positional accuracy of human population distribution.

As for GRUMPe—the mechanism through which the modeling occurred—it proved to be a good tool to refine GPW in countries where administrative data is coarse. Although the administrative data in Colombia is relatively good, the size of the units is such that the reallocation works very well. As shown in Figure 3, there are cases of relatively large administrative units with one or two cities within, and we can clearly see how the GRUMPe assigns people to the urban areas, decreasing the density of the remaining administrative unit. Then, there are cases, like Cali, where the urban areas identified by the lights expand over several administrative units. Also in this case, the reallocation process outputs a population distribution that is more consistent with the notion that people tend to be more concentrated into the urban areas rather than uniformly distributed across an administrative unit. GRUMPe also proved to be an effective way to compensate for the blooming effect in some countries where administrative data include city boundaries. In this case the total population allocated to the light is larger than the census value for the same city, but, given the type of administrative data, the result is a structure that has a more densely populated urban core at the center of the light, surrounded by a lower-density outskirt, as shown in Figure 4.

We also have found some instances where GRUMPe does not work as effectively as in other cases. First, in countries such as Malawi, where GPW is very detailed, there are more than 9,000 administrative units, but only about 40 urban extents, most of them very small. Therefore GRUMPe does not provide any additional information on population distribution. This is not so much of a problem, rather than noteworthy for consistency sake, since most countries do not have such high-resolution data. Another example of the GRUMPe limitations is related to small, populated islands, like several islands in the Caribbean or in the Pacific. These islands might have one or two isolated small urban centers, but, due to the blooming effect, appear all lit. In this case, the reallocation of the population into urban areas and rural areas is not very effective, as the urban areas identified by the lights could cover the entire islands, even though the urban population is a fraction of the total population, and the administrative data is generally good. Fortunately, inputs in the underlying administrative and population data for GPW v3 have improved substantially for more than half of the world's island nations (Balk and Yetman, 2004). Where the administrative data are poor in the sense that they attempt to approximate urban centers, but do so inadequately (e.g., the construction of small triangular shapes to represent urban centers in the former Soviet republics) and the lights data are moderate to poor, GRUMPe may assign too high a population density value to such a small area. In this case, its general assignment is correct, but the extent is limited both by the lights and the administrative data's shortcomings.

In sum, GRUMPe performs moderately well. Where administrative data and the lights data are good, GRUMPe does not perform very well. However, in these instances, there is less imperative for it to work well; it is only a problem in the event that it introduces error or degrades the data quality, both open questions at this point. Where administrative data are moderate or poor, and the lights (and more intensive substitutes) are moderate to good, GRUMPe performs very well. Where both the administrative data and the lights (or its substitutes) are poor GRUMPe just does not have much to work with. As is generally the case, there are no perfect substitutes for good data.

The main challenge of this methodology, is the complex and time-consuming procedure that goes from collecting and processing the census data, to combining the city population with the spatial information about the settlements and finally to reallocating people from the administrative units into the urban centers. Some of that complexity could be reduced as institutional capacity increases in the production and distribution of urban data, as has already happened for administrative data over the past 10-15 years (see Balk and Yetman, 2004). Further gains may be made by establishing international guidelines on the definition and correspondence between metropolitan areas of different types (see Champion and Hugo, 2003). In hindsight, such guidelines would make an invaluable contribution in reducing the processing time, but also increasing the accuracy of the underlying point data, upon which both the extent mask and population surface are based. Finally, even though we estimated population for three time periods (1990, 1995, and 2000), users need to remember that the lights refer to one point in time only (the 1994/1995 time period), therefore it would not be advisable to use these extents for any analysis of change in spatial parameters.

The power of these new data, shortcomings and all, are in its applications. One such application has been undertaking by the Millennium Ecosystem Assessment where by the urban extent mask and this new 1 km gridded population surface are overlaid with ecosystem boundaries (McGranahan *et al.*, 2005). That analysis shows that coastal and island systems tend to be the most densely populated, followed by systems with water and other agricultural resources—namely, cultivated and inland water systems—but that in coastal areas, land area is disproportionately urban. Two systems—coastal and cultivated—also sustain high rural population densities. Forested and mountain ecosystems, which sustain the same total population as coastal ecosystems are much less urban, and thus sustain much lower population densities, even its urban areas. These data suggest that roughly 3% of the earth's surface is occupied by urban areas, a large share of which concentrated in coastal and cultivated environments, much greater than the often-cited suggestion of 1-2% of land area. It is noteworthy that although the highest share of urban land area is in the coastal zone (10.2%) is coupled with the highest share of urban population (64%), cultivated systems have 6.8% of their land area in cities, perhaps somewhat surprisingly. These areas are somewhat less urban (44.9%) other ecosystems, such as islands and water, with smaller shares of land going to urban area. Although many cultivated areas explicated omit urban centers from their ecosystem, smaller settlements, and the periphery of large settlements are commonly found in cultivated zones.

These data can also be used to provide much greater information on distances to urban areas, where the places can be classified according to information about their population and geographic size. Much attention has been made on the importance of moving toward an urban continuum (NRC, 2003, Woods, 2003) and these datasets are a first big step in moving in that direction. These data have already been used in studies of mortality (Balk *et al.*, 2004) and hunger in Africa, by combining these data with household survey data. Other early uses of the data have been to use the population surfaces in assessing malaria risk (Hay *et al.*, 2004) and dimensions of rurality (Chomitz *et al.*, 2005). Continued uses will assist in contributing to the dialogue on how best to collect, interpret, and process information to maximize flexible and creative new uses of these data.

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