Modeling Day- and Nighttime Population Exposure at High Resolution: Application to Volcanic Risk Assessment in Campi Flegrei

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ABSTRACT

Improving analyses of population exposure to potential natural hazards, especially sudden ones, requires more detailed geodemographic data. Availability of such information for large areas is limited by specific database requirements and their cost.

This paper introduces and tests a new approach for refining spatio-temporal population distribution at high resolution by combining diverse geoinformation layers. Its value is demonstrated in the context of disaster risk analysis and emergency management by using the data in a real volcanic risk scenario in Campi Flegrei, located within the metropolitan area of Naples, Italy. Results show that there is significant variation in exposure from nighttime to daytime in the study area.

The proposed modeling approach can be applied and customized for other metropolitan areas, ultimately benefiting disaster risk assessment and mitigation.

Keywords

Population exposure, dasymetric mapping, GHSL, EMS2013, NDPop, volcanic risk, Campi Flegrei.

INTRODUCTION

Analysis of natural disaster risk is hardly complete without assessment of potential or effective population exposure, and this task can support decision-making at several stages of the emergency management cycle (Freire, 2010). The ongoing processes of urbanization and population growth put more people in harm's way, generating and increasing risk levels in many areas.

Accurately estimating population exposure is an essential element of effective risk analysis and emergency management (FEMA, 2004). Such analyses are supported by population distribution maps, but these should be produced at appropriate spatial and temporal scales (Sutton, Elvidge, and Obremski, 2003). The quality and level of detail of population data has a direct effect on response and lives saved. Especially in emergency situations, it is preferable to have data at highest possible spatial resolution (NRC, 2007).

Population grids represent both population distribution and density and can be easily combined with hazard maps for exposure assessment or modeling. Since hazard events can occur at any time and with little forewarning, there is a need for population distribution data that goes beyond a residence-based (i.e. nighttime) representation.

Recent efforts at improving the temporal representation of population distribution include those of McPherson and Brown (2004), the LandScan USA project (Bhaduri, Bright, Coleman and Urban, 2007), the Population 24/7 (Martin, Cockings and Leung, 2010), and the DynaPop model (Aubrecht, Steinnocher and Huber, 2014). Such models typically rely on intensive geospatial and statistical databases usually only available for selected areas, and often at a high cost. However, the current modeling capabilities of Geographic Information Systems (GIS) combined with recent availability of detailed spatial datasets, enable the exploration of new approaches to the challenge of population distribution mapping.

Dasymetric mapping is a powerful cartographic technique, originally used for population mapping, which aims at limiting the distribution of a variable to the areas where it is present, by using related ancillary information in the process of areal interpolation (Eicher and Brewer, 2001). Critical to the success of this technique is the quality of the ancillary information and especially the covariate that will support population disaggregation. The recent Global Human Settlement Layer (GHSL) project has undertaken unprecedented mapping and quantification of built-up areas, at continental and global level, using satellite imagery and innovative information extraction approaches (Pesaresi and Ehrlich, 2009). This data may prove to be a superior covariate for population distribution modeling.

Volcanic eruptions are among the most destructive natural hazards, capable of causing great devastation and loss of life. These phenomena can be sudden, time-specific events, for which analysis of potential exposure and risk should be prepared beforehand and kept up-to-date. For the same volcano, eruptive events can also vary widely in magnitude and be affected by different environmental conditions, originating quite specific hazard zones having varying dimensions.

Many human settlements, from small villages to whole metropolitan areas, are located in the vicinity of active or dormant volcanoes. Assessments of potential worldwide population exposure to volcanic hazard have been conducted using globally-available population grids (Small and Naumann, 2001; GFDRR, 2011). However, even the highest spatial resolution of those grids (i.e., 30’’of LandScan) is too coarse for combining with specific and detailed local-level hazard zones, and its representation of “ambient population” corresponds to a temporal averaging that is not ideal for using in time-specific hazards.

The Campi Flegrei volcanic field, located in the south of Italy, is among the largest in the world. It is characterized by very high volcanic risk (Rossano, Mastrolorenzo and De Natale, 2004), due to the location within Naples’ metropolitan area, just circa 20 km to the east of the infamous Vesuvius.

This volcanic field has been the subject of recent risk assessment, but only considering economical exposure for the city of Naples (Alberico, Petrosino and Lirer, 2011). Another recent study has modeled and analyzed the vulnerability for evacuation, but limited to resident population (Alberico, Petrosino, Maglione, Bruno, Capaldo, Dal Piaz, Lirer and Mazzola, 2012). The availability of a recent map depicting hazard levels at local scale provides an opportunity to develop and integrate improved population distribution data in the analysis of volcanic exposure for a large urban area.

This paper aims at (1) presenting a new approach for modeling spatio-temporal population distribution at high resolution (the *NDPop* model) and (2) illustrating its value in the context of EM and risk analysis, by using the data in an actual volcanic risk scenario.

STUDY AREA AND DATA

The study area for population modeling and application corresponds to the Large Urban Zone (LUZ) of Naples, Italy, as defined for Urban Atlas mapping. This area is part of the metropolitan area of Naples, and contains the Campi Flegrei volcanic field, one of the world's super-volcanoes. The study area occupies about 567 km^2, and encompasses 37 communes having a total resident population of 2,212,832 (2011).

Several geospatial datasets were combined to model population distribution. Their main characteristics are listed in Table 1.

Data set	Source	Date	Data type
ESM 2013	EC-JRC, IPSC	2011-2012	Raster (10 m)
Urban Atlas (UA)	EEA	2005	Vector polygon
LandScan 2012	ORNL	2012	Raster (30'')
Population census (Italy)	ISTAT	2011	Vector polygon
Daytime W/S weights	Previous study (Freire, 2010)	2001	Tabular

Table 1. Main input datasets used in modeling population distribution

ESM 2013: The European Settlement Model (ESM) is an output of the Global Human Settlement Layer (GHSL) project. This model (Figure 1) produces a seamless 10m-resolution raster mosaic of built-up (BU) for the whole Europe representing, for each cell, the ratio of surface area covered by building structures (Ferri et al., 2014). It was recently produced at the European Commission's Joint Research Centre from 2.5 m SPOT imagery.

Urban Atlas (UA): The Urban Atlas project (EC, 2011) maps land use using visual analysis for a large set of European cities (695 in 2012) including Naples. The nomenclature has 19 thematic classes (in 2006) and has a MMU of 0.25 ha (for 'Artificial surfaces'). Data is provided free of charge by the European Environment Agency (EEA) through its online portal.

LandScan (LS): The LandScan Global Population Project (Dobson, Bright, Coleman, Durfee and Worley, 2000), based at the Oak Ridge National Laboratory (USA) outputs a 30 arc-second grid of ambient population distribution, updated annually. We used LS2012, released in 2013, to try to ensure that the 2011 round of censuses was incorporated in the layer.

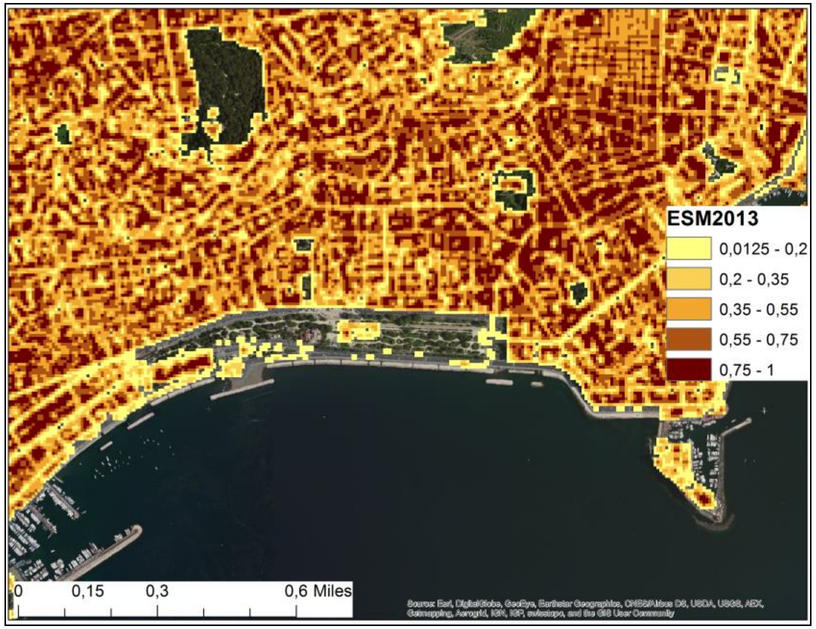

Figure 1. ESM2013 10-m layer depicting built-up in Naples, overlain on satellite imagery

Population census: Census data for 2011 was produced by the Italian National Institute of Statistics (ISTAT, 2011) and made available online as polygons and tables from the level of census tract (*sezione*).

Daytime W/S weights: The values used as reference for the densities of commuting workers and students (W/S) per UA land use class were obtained from a previous study using activities' address points (Freire, 2010).

A map of volcanic hazard was also identified for the Campi Flegrei volcanic field and digitized for this work (Figure 2).

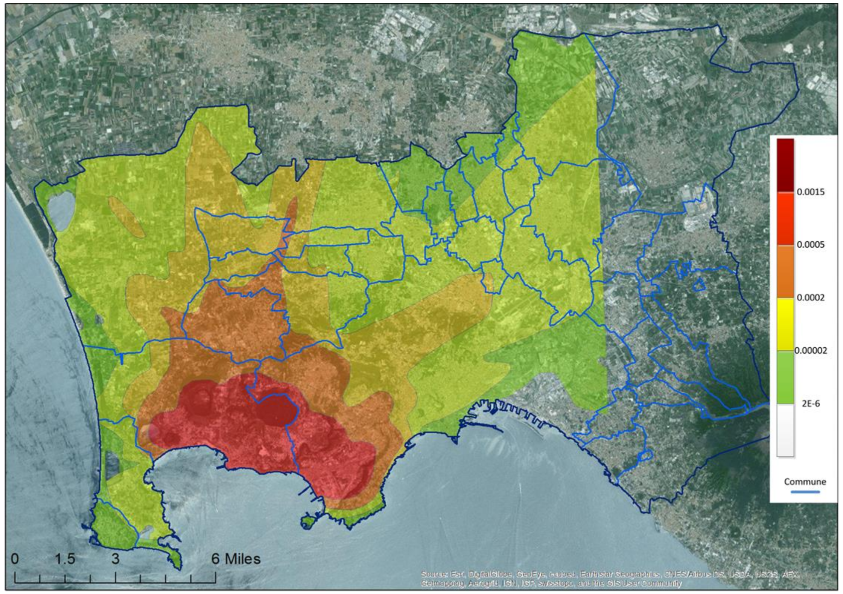

Figure 2. Study area and hazard map for pyroclastic currents in Campi Flegrei, overlain on satellite imagery

The hazard model was produced by Rossano et al. (2004), which have authored the first physically based estimate of hazard from pyroclastic flows, in the form of probabilities of pyroclastic density currents (PDC). A pyroclastic density current is a fast-moving current of hot gas and rock, and the PDC hazard map depicts the probability that an area experiences a PDC in a given time interval. The hazard map of the Campi Flegrei volcanic field was calculated from the eruption rate in the last 12,000 years by means of a numerical simulation of both concentrated and dilute gravity-driven pyroclastic flows on a digital topographic model. According to this map, maximum hazard appears to be in the NE sector of the caldera (Rossano et al., 2004)

MODELING AND ANALYSIS

Modeling daytime and nighttime population distribution at high resolution

The developed model for night- and daytime population distribution (*NDPop*) is based on raster dasymetric mapping, using BU cells from ESM as target units to which population counts are re-allocated (Figure 3). The model was implemented in GIS using six datasets as inputs: LandScan population grid, reference densities of W/S by land use class (LU weights), Urban Atlas (UA) land use map, GHSL/ESM BU grid, official census data, and the ratio (or %) of residents commuting for work or study.

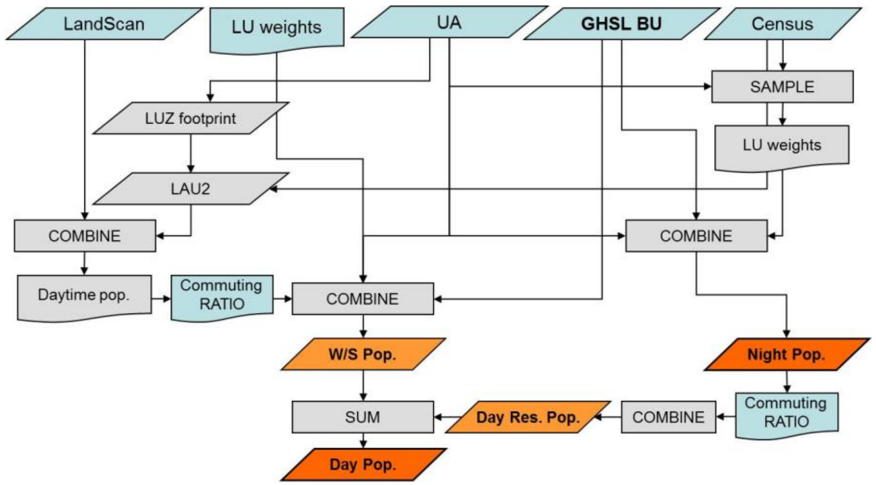

Figure 3. Generalized flowchart of the NDPop population model (inputs in blue, outputs in orange)

Disaggregation of population from source zones (LAU2 or census tracts) is based on the ‘intelligent dasymetric mapping’ approach proposed by Mennis and Hultgren (2006). In each combination of source zone/LU class, final population density of the cell is proportional to its BU density.

The nighttime (residential) population layer is produced by disaggregating finest census counts (tracts for Naples) to ESM cells, informed by land use. Census zones are sampled (with the containment rule) in UA to derive overall density weights per LU class for the study area. These weights are then used to disaggregate census resident population counts to ESM BU cells. In this process, no LU classes are selected or masked *a priori*, instead their eligibility and specific weights are determined by the sampling process.

The daytime population layer results from the combination (arithmetic sum) of two grids: the worker/student population (W/S) grid and the daytime residential population grid. The W/S layer is generated by first inferring the daytime population per Local Area Unit (LAU2 or commune) study area. This is done by summarizing the population of LandScan within sufficiently large administrative units. Assuming that LS is an averaged measure of mostly night-day periods considering places of residence and activities, and knowing the nighttime population from census, an indication of daytime population can be derived. This value is then multiplied by the ratio of people commuting in each unit to estimate the number of commuting workers and students. This count is then disaggregated to ESM cells considering their land use class and respective reference densities of W/S, to produce the W/S population layer.

The commuting ratio is also combined with the nighttime (residential) population grid to derive the daytime residential population layer. In the implementation for Naples, two variables were not specific for the study area: LU weights for W/S, and commuting ratios.

Using this methodology, four raster population distribution surfaces were produced, at 10 m resolution: (1) nighttime (residential) population, (2) daytime residential population, (3) daytime worker and student population, and (4) total daytime population. These grids were aggregated to 50 m cell size for subsequent analyses and visualization.

The modeled population surfaces represent maximum expected densities on a typical workday, assuming that all residents are at home at night and all workers and students are in their workplaces and schools, and the remainder in their residences during the daytime period. Although this is still a simplification of reality, it is a significant improvement over data sets based on censuses alone.

Nighttime and daytime grids can be further combined to create temporally-weighted measures of population density at high resolution, to represent other temporal cycles (e.g. weekly, seasonal).

The approach refines representation of population distribution and densities respective to the input datasets: nighttime (residential) population distribution is more detailed than the census, whereas daytime distributions were previously inexistent.

Nighttime and daytime population exposure to volcanic hazard

Population exposure to the PDC in the Campi Flegrei volcanic field was assessed in GIS using zonal analysis, for the area of intersection of hazard map and communes considered for population modeling (about 410 km^2 - see Figure 2). The 50-m night- and daytime population surfaces were summarized by volcanic hazard zone in each potentially affected commune, labeling the original hazard classes from ‘1’ (lowest) to ‘6’ (highest).

The results of the exposure analysis are summarized in Table 2.

	Study Area	Nighttime Population		Daytime Population		Difference
Hazard level	Rel [%]	Abs. [Pers.]	Rel. [%]	Abs. [Pers.]	Rel. [%]	Rel. [%]
1	3.2	74,166	4.1	111,820	6.0	50.8
2	14.9	237,974	13.2	329,315	17.7	38.4
3	42.7	892,028	49.4	839,004	45.0	-5.9
4	18.6	281,496	15.6	259,830	13.9	-7.7
5	11.6	211,235	11.7	189,480	10.2	-10.3
6	9.1	107,258	5.9	136,000	7.3	26.8
Total	*100*	*1,804,157*	*100*	*1,865,449*	*100*	*3.4*

Table 2. Population potentially exposed to PDC hazard levels in nighttime and daytime periods within the study area.

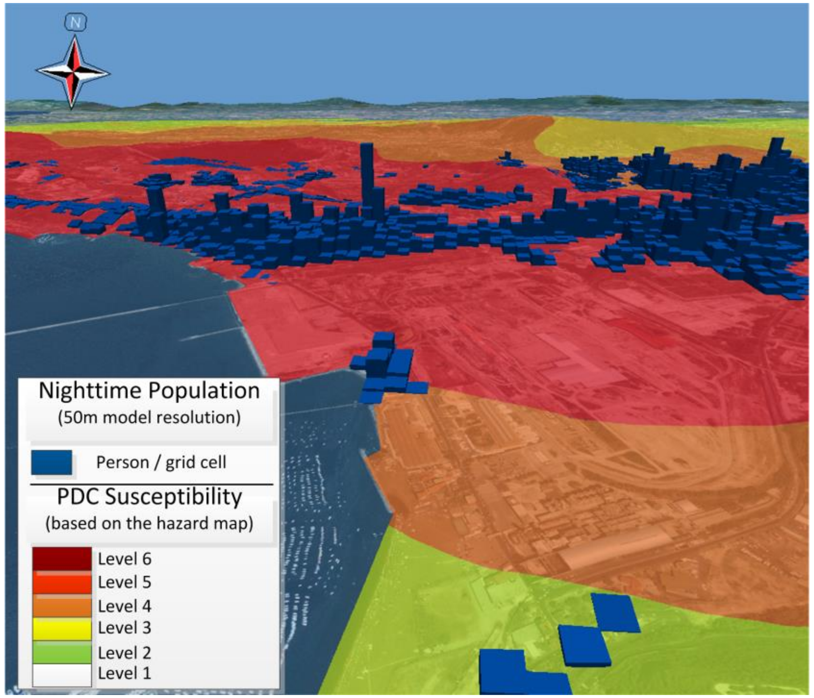

Figure 4. Modeled nighttime population densities (at 50 m) and volcanic hazard zones in Campi Flegrei

There are significant differences in potential exposure from night- to daytime, in all hazard levels. Although the majority of the population exposed is associated with the hazard levels '3', '4', the population within the zone of the highest hazard level ('6') is noteworthy and increases markedly (27%) from nighttime to daytime. Also, great variation in potential population exposure from night- to daytime periods can be observed in the zones of hazard levels '1' and '2', as much as 51%.

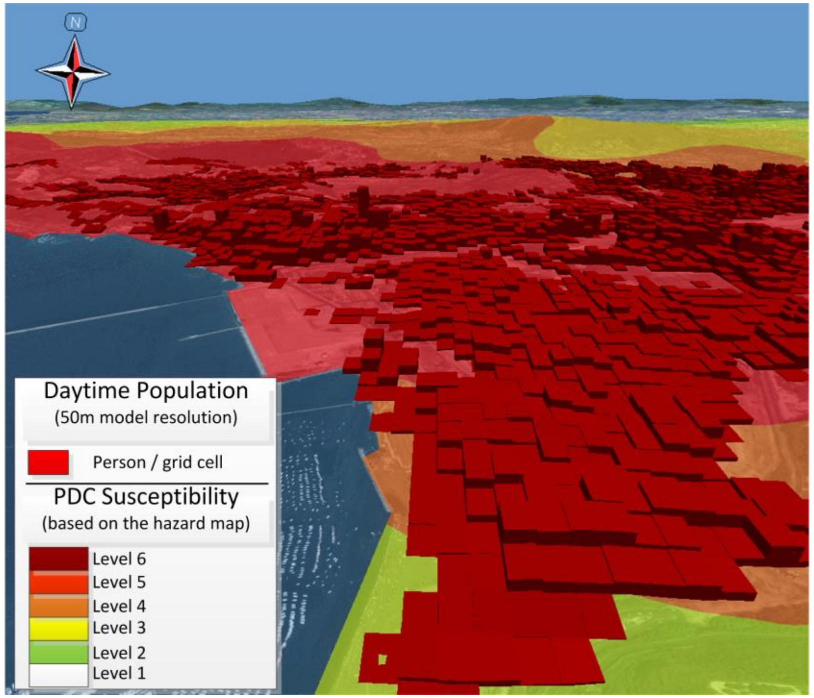

Figure 5. Modeled daytime population densities (at 50 m) and volcanic hazard zones in Campi Flegrei

The population estimated to be present in hazard zones '3' to '5' is greater during the night. The zones '5' and '6' contain about 18% of the total population in both periods, more than 300,000 people, with potential exposure to highest volcanic hazard increasing by 27% from night- to daytime.

Overall, in the area under analysis, the estimated daytime population present is slightly higher (3%) than the resident population, reflecting the gravitational pull exerted by the city of Naples as important economical center of the region. Figures 4 and 5 illustrate in 3D for part of the study area the varying population distribution and densities in nighttime versus daytime periods in each volcanic hazard zone.

CONCLUSIONS AND OUTLOOK

Enhanced geoinformation on population is needed to improve assessment of exposure to natural hazards. A novel modeling approach (*NDPop*) was presented that enables refining population distribution in space and time, by combining existing statistics and spatial datasets. Notable among the latter is the recent availability of a detailed layer mapping and quantifying built-up, the ESM 2013.

The main contributions of the NDPop model are the addition of a temporal dimension to population data and the refinement of the spatial distribution, for areas where detailed statistics do not exist or are not available. The model is scalable, can be extended to other cities and tuned with local parameters, when available.

The obtained high-resolution datasets of nighttime and daytime population were combined with volcanic hazard zones to estimate human exposure in those periods, in the Campi Flegrei area. The analysis shows that a significant amount of population is potentially at risk, and that this exposure varies significantly from night- to daytime. Potential exposure to highest hazard level is greatest in the latter period.

The approach can be valuable for disaster risk analysis and EM at high resolution for all hazard types, especially those that can affect local areas as small as a city block. Future work will extend and test the model in other urban areas and scenarios, and will include validation of the results. The creation of additional spatio-temporal segmentations of population, such as nighttime worker population, will also be experimented.

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