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Assessment of PM Exposure at intra-urban scale in preparation of MAIA mission (APEMAIA) Project

WP2104 – PM2.5 and PM10 population exposure

DEL010 – Description of the third system module (WP2) for the analysis of population exposure to PM2.5 and PM10 at high resolution (SW007 and SW008)

Contract n. 2023-39-HH.0

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ASI CONTRACT N°	2023-39-HH.0		
PROJECT NAME	Assessment of PM Exposure at intra-urban scale in preparation of MAIA mission (APEMAIA)	CONTRACTOR	National Research Council – Institute of Atmospheric Pollution Research
PROJECT MANAGER	Maria Adamo (CNR-ITIAm)	DATE SUBMITTED	N/A
AUTHOR	M. Aquilino, Marica De Lucia, Delia Evelina Bruno, M. Adamo, Silvana Fuina, Cristina Tarantino (CNR-ITIAm)	CONTRACTOR'S REFERENCE	Issue:01 Rev.:01 Date:25/09/26
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EXECUTIVE SUMMARY		
The DEL010 deliverable describes the implementation of the third APEMAIA system module, developed to assess population exposure to PM_{2.5} and PM₁₀ at the intra-urban scale. High-resolution PM concentration products were integrated with population data redistributed to a regular grid using the CNR-IIA vector-based dasymetric method, based on census data, building footprints, building height or volume, and building use. The primary assessment method is the Population Weighted Exposure Level (PWEL), consistent with the population-weighting principle of SDG indicator 11.6.2. PM concentrations and resident population were combined on a common 300 m grid for Bari over the 2019–2022 period. Cell-level exposure contributions were then aggregated to a 900 m grid and normalised by the corresponding population to obtain local population-weighted mean concentrations. The same contributions were aggregated at city scale to calculate the annual PWEL. A complementary exploratory analysis was conducted to investigate exposure patterns among demographic groups and across different urban and land-use contexts. This component is distinct from the SDG indicator and is intended as a relative spatial-screening tool rather than an estimate of individual dose or absolute health risk. Finally, annual population-weighted concentrations were classified using the 2021 WHO Air Quality Guideline levels and interim targets to identify areas requiring greater attention. Overall, the module provides a consistent multiscale framework for producing cell-level exposure contributions, intra-urban population-weighted maps and city-scale indicators, while supporting the identification of spatial and demographic inequalities in exposure.		
NAME OF ASI PROJECT MANAGER	Name Surname (PM) Name Surname (RUP) Name Surname (Project Scientist)	
STAR CODE		No OF VOLUMES:

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1 AIM OF THE DOCUMENT

This final version of DEL010 documents the methodology implemented within WP2104 – PM2.5 and PM10 population exposure – and the results obtained for the Bari study area. The deliverable describes the generation of high-resolution population distribution layers and their integration with PM concentration products to assess population exposure at the intra-urban scale.

The methodology follows the APEMAIA project proposal, in which population-weighted exposure was identified as a key project output (P3). Census population data were spatially disaggregated using the CNR-IIA dasymetric method and combined with PM2.5 and PM10 concentration maps to calculate the Population Weighted Exposure Level (PWEL), consistently with the population-weighting principle of SDG indicator 11.6.2. A complementary exploratory analysis was also conducted to examine exposure patterns across demographic groups and different urban and land-use contexts.

The preliminary release of DEL010, issued at T0+7M, focused on population-density mapping. This final release consolidates the complete workflow, including population mapping, cell-level exposure contributions, local population-weighted concentrations, city-scale PWEL estimates and the classification of annual exposure levels according to the 2021 WHO Air Quality Guidelines and interim targets. The resulting products support the analysis of spatial and demographic differences in PM exposure within the study area.

The methodology follows the approach defined in the APEMAIA project proposal, where population-weighted exposure was identified as a key project output (P3). The proposal specifically envisaged the use of census data disaggregated through a dasymetric method and the computation of the Population Weighted Exposure Level (PWEL) as an implementation of SDG indicator 11.6.2.

1.1 Applicable and reference documents

This document incorporates provisions from other dated or undated documents. These references are cited at appropriate places in the text and are listed hereafter. For undated references, the latest edition of the publication referred applies.

In case of conflict between two or more applicable documents, the higher document will prevail.

1.1.1 Applicable documents

[AD 1] ASI Contract No. 2023-39-HH.0

[AD 2] DEL_004 – Technical Report “User Requirement Document (preliminary version)”

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- [AD 3] DEL_008 – Description of the first system module (WP2) for the extraction of high-resolution AOD maps (SW004); description of the Data-driven and Knowledge-Driven procedures for the extraction of LCLU maps in urban areas (SW005) (preliminary version)
- [AD 4] DEL_009 – Description of the second system module (WP2) for the estimation of PM_{2.5} and PM₁₀ at high resolution (SW006) and analysis of relations between urban heat islands and intra-urban scale pollution
- [AD 5] DEL012 – Validation report

1.1.2 Reference documents

- [RD 1] WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.
- [RD 2] Aquilino, M., Adamo, M., Blonda, P., Barbanente, A., Tarantino, C., 2021. Improvement of a Dasymetric Method for Implementing Sustainable Development Goal 11 Indicators at an Intra-Urban Scale. *Remote Sens.* 13, 2835. <https://doi.org/10.3390/rs13142835>.
- [RD 3] United Nations Statistics Division, 2023. SDG Indicator 11.6.2. Metadata: Annual Mean Levels of Fine Particulate Matter (e.g. PM_{2.5} and PM₁₀) in Cities (Population Weighted). Available at: <https://unstats.un.org/sdgs/metadata/files/Metadata-11-06-02.pdf>
- [RD 4] Mennis, J., 2003. Generating Surface Models of Population Using Dasymetric Mapping. *The Professional Geographer* 55(1), 31–42. <https://doi.org/10.1111/0033-0124.10042>
- [RD 5] United States Environmental Protection Agency, 2011. Exposure Factors. Handbook: 2011 Edition. EPA/600/R-09/052F. Washington, DC: U.S. Environmental Protection Agency. Available at: <https://iris.epa.gov/Document/%26deid%3D236252>
- [RD 6] European Commission, Joint Research Centre, 2022. ExpoFacts: European Exposure Factors Sourcebook. Available at: https://joint-research-centre.ec.europa.eu/expofacts-european-exposure-factors-sourcebook_en
- [RD 7] ISPRA, 2025. Esposizione della popolazione agli inquinanti atmosferici outdoor - PM₁₀. In: *Ambiente in Italia 2025*. Roma: Istituto Superiore per la Protezione e la Ricerca Ambientale.

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1.2 Acronyms and abbreviations

Table 1-1 provides the acronym list.

Table 1-1: Acronyms and abbreviations

Acronym	Description
AI	Artificial Intelligence
APEMAIA	Assessment of PM Exposure at intra-urban scale in preparation of MAIA mission
ARPA Puglia	Apulian Regional Agency for Environmental Protection
ISTAT	Italian national institute of STATistics
ML	Machine Learning
PM	Particulate Matter
PWEL	Population Weighted Exposure Level

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2 Population mapping

The preliminary version of DEL010, issued at T0+7M, documented the CNR-IIA vector-based dasymetric method and its application to the generation of high-resolution population-density maps. This section recalls the main input datasets and documents the updates and spatial-processing steps required to integrate the population layers with the PM_{2.5} and PM₁₀ products generated within WP2103.

To achieve the goals of WP2104 - HR PM_{2.5} and PM₁₀ population exposure, the first step involves obtaining a realistic population density map of the study areas.

The population component is based on census data redistributed to a regular 100 × 100 m grid using the CNR-IIA vector-based dasymetric method described in the preliminary version of DEL010 and reported in 2.1 subsection.

The spatial distribution of population is specifically considered as an essential variable requested for quantifying SDG 11 indicators. The SDG 11.6.2 on the annual mean levels of particulate matter PM₁₀ and PM_{2.5} (population weighted) can be specifically computed by a spatial overlay of grid population density map with air pollution information maps [RD 1].

2.1 The CNR-ITIAm vector-based dasymetric method

Demographic data are usually represented by a choropleth map where the statistical data are aggregated with census area. This type of representation is reported to have several limitations with respect to spatial analysis and population distribution (Mennis 2003). To overcome this issue CNR-ITIAm developed an automatic workflow that implements a reproducible dasymetric mapping method [RD 2]. Dasymetric mapping refers to a technique used to distribute population data more accurately across a geographic area: typically, by identifying natural spots of concentration and rarefaction based on supplementary data (like land use or satellite imagery).

Specifically, CNR ITIAm method combines census counts with building footprints, building height or volume, and building-use information. The resulting grid values represent the estimated number of residents allocated to each cell, rather than population density per unit area. The rationale behind this weighting procedure is to account for the fact that, due to multi-floor buildings, population density values are generally higher in urban areas than in rural contexts.

The criteria proposed to define the weights of population re-distribution are described as follows:

- In residential areas, population allocation is proportional to Building Footprint Areas/Volumes.

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- In non-residential areas, population allocation in a specific cell depends also on building use and relative correction factors.

To facilitate the exploitability and interoperability between models and the reproducibility of the results, the dasymetric mapping model developed by CNR-IIA has been published using the [Virtual Earth Laboratory \(VLab\)](#) framework, in two versions (a basic and an advanced one for expert users). The code was written in Python 3.7 programming language by mainly using pyQGIS libraries for Python 3.7. shows the main differences between the basic and advanced versions and the links to the respective GitHub repositories.

Table 2-1. Differences in setting options between basic and advanced workflow implementations.

Setting options	Dasy2 (Basic implementation)	Dasy3 (For advanced users)
	https://github.com/MarA-ii/DasymetricV2.2	https://github.com/AM-IIA/Dasymetric3.git
Building use layer	Urban Atlas as input, Building use classes not configurable	Generic Land Use map, Building use classes configurable
Building heights	Required	Optional
Weight's correction factors	Fixed	Configurable

The option “Volumes” has been introduced in 2.0 version of the dasymetric method, and it is applicable when Building Heights data are available. The introduction of building height information can discriminate between residential areas of greater or lesser density.

An experimental plugin for QGIS was also developed as an additional open-source tool for sharing the dasymetric method with QGIS community users, which include urban planners, statisticians, technical employees of local and regional authorities. Dasy QGIS Pugin is available at official repository of QGIS as an experimental plugin: <https://plugins.qgis.org/plugins/dasy/#plugin-details>.

The first step of the dasymetric method consists of a double intersection of the input vector information layers: polygons of census areas; polygons of different building uses and the final output grid. The elements resulting from such double intersections are shown in Figure 2-1. The colours represent the different building uses. The red strokes identify the polygons of the census areas, while the blue strokes delimit the output grid cells.



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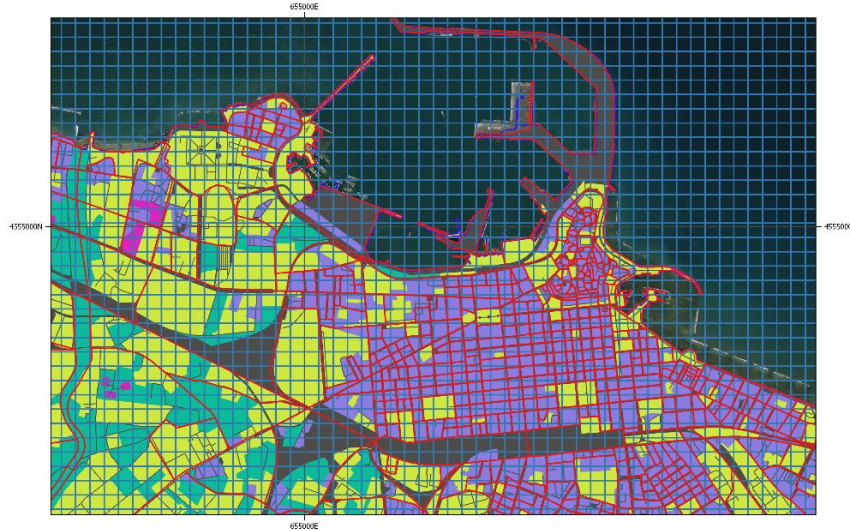


Figure 2-1 Double intersection of input vector layers [RD 2].

The following formula reflects the dasymetric computation method implemented in the QGIS environment:

$$P_{grid} = \sum_{j=1}^m P_{j,census} \frac{\sum_{i=1}^n BF_{sub_elemGRID_i} * Hmean_{sub_elemGRID_i} * Corr_{factor}}{\sum_{l=1}^k BF_{sub_elemCENSUS_l} * Hmean_{sub_elemCENSUS_l} * Corr_{factor}} \quad (1)$$

where,

- $BF_{sub_elemCENSUS_l}$ is the built-up footprint area in a generic sub-element l of a census zone having different building use;
- k is the number of census zone sub-elements with different building use, derived from the intersection of vector layers census zones and building use;
- $BF_{sub_elemGRID_i}$ is the built-up footprint area in a generic sub-element i of a census zone, with different building use, included in the output cell considered;
- n is the number of census zones sub-elements, with different building uses, within a grid cell, derived from the double intersection;
- $P_{j,census}$ is the population of a generic census zone;
- m is the number of census zones in a cell;
- P_{grid} is the final population allocated to a cell of a regular grid;
- $Hmean_{sub_elemGRID_i}$ is a mean value of building heights of sub-elements in a cell. The constant value 1.0 was set for the dasymetric method (version 1.0);

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- $Hmean_{sub_elemCENSUS_i}$ is a mean value of building heights in census zones. The constant value 1.0 was set for the dasymetric method (version 1.0);
- $Corr_{factor}$ are correction factors based on building uses, as documented in [RD 2].

The block diagram of the version 2.0 software implementation in the QGIS environment (compatible with Python 3.7.) is shown in Figure 2-2.

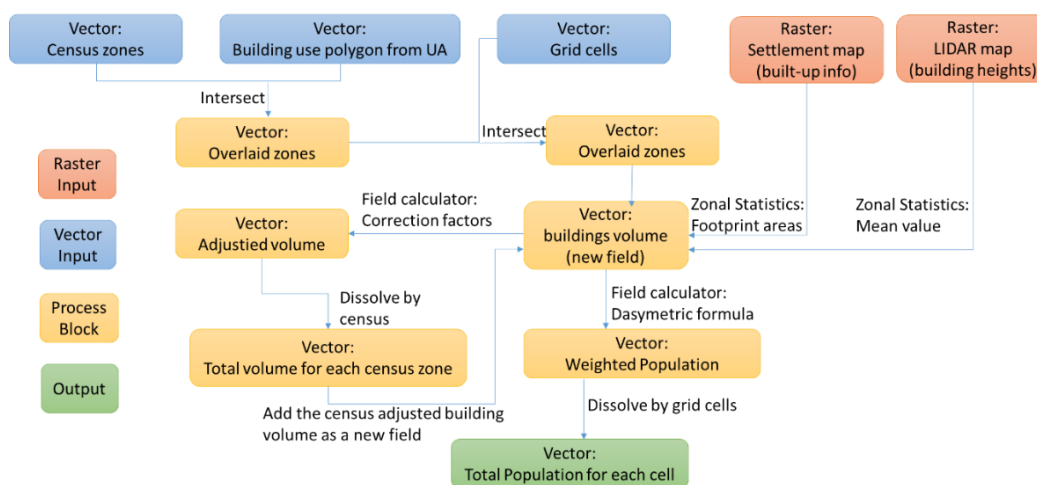


Figure 2-2- Dasymetric 2.0 version [RD 2].

2.2 Step-by-Step process to generate density population map in the study areas

For APEMAIA project we have chosen to use a QGIS implementation plugin, specifically the Dasy plugin, for generating grid-based population density maps for each area of study.

Here's a summary of Step-by-Step process that need to be carried out for APEMAIA project:

- Access the Plugin:** The plugin, known as Dasy, is available in the QGIS Plugin Repository and can be found at this link: <https://plugins.qgis.org/plugins/dasy/#plugin-details>
- Install the Plugin:** Open QGIS (a popular open-source geographic information system). Navigate to the Plugins tab and search for "Dasy" in the repository. Install the Dasy plugin to integrate it into your QGIS environment
- Gather relevant geospatial data for the area of study such as:**
 - Population data, usually in the form of census data, with counts at a coarse resolution (e.g., city level, district level).
 - Administrative boundaries of the study areas.

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- Land use/land cover data or other auxiliary data that help refine the population distribution.
- Digital elevation model/building heights of the study areas (optional input).

The official source of population census data in Italy is ISTAT (Italian national institute of STATistics).

ISTAT provides the results of the **permanent census of population and housing** for the following sub-municipal territorial levels:

- **Census sections** for all Italian municipalities.
- **Sub-municipal administrative areas**, where such partitions exist.

The last update dataset (after the oldest, in 2011) refers to the census population as of **December 31, 2021**. Databases provide also new layers on the administrative boundaries: **2021 Territorial Base**. These bases reflect updates to municipal demography and territorial changes that occurred since the 2011 census.

The first digits of the census section codes correspond to the municipalities as they existed on **December 31, 2021**. While the data structure has been made consistent with past censuses, direct comparability is not guaranteed due to changes in territorial boundaries and population allocation methods. The census provides information on population variables, including sex, age, citizenship, education, employment, and households. Additionally, the number of occupied dwellings is included. Such categorization is very important in the light to carry on an exposure analysis tailored to the most vulnerable group of the urban population.

An update of land cover map has been incorporated as reported in [AD 3]. Building information has been extracted from Copernicus Urban Atlas dataset.

The source of average building heights is DTM and DSM will be obtained for the study areas. For Bari site they have been generated from a PLEIADES stereo image acquired in July 2021. However, for all the study areas, a DTM and DSM for 2008 can be obtained from LiDAR data provided by the Ministry of the Environment's Extraordinary Remote Sensing Plan. It is planned to request LiDAR data for the Taranto and Rome study areas.

The choice of evaluating heights as an average value in the LiDAR data (dated 2008) is a criterion that is useful to overcome the issue of missing information for buildings constructed after 2008. Such an approximation is justified by the existence of municipal regulations that prevent the construction of new buildings with height values differing from those prevailing in the urban context.

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For Bari site the acquisition of new 2021 population updated dataset is completed. In addition, for this site, a dataset for population dates back to 1 January 2020 is available (obtained through direct interaction with the Municipality of Bari, Figure 2-3).

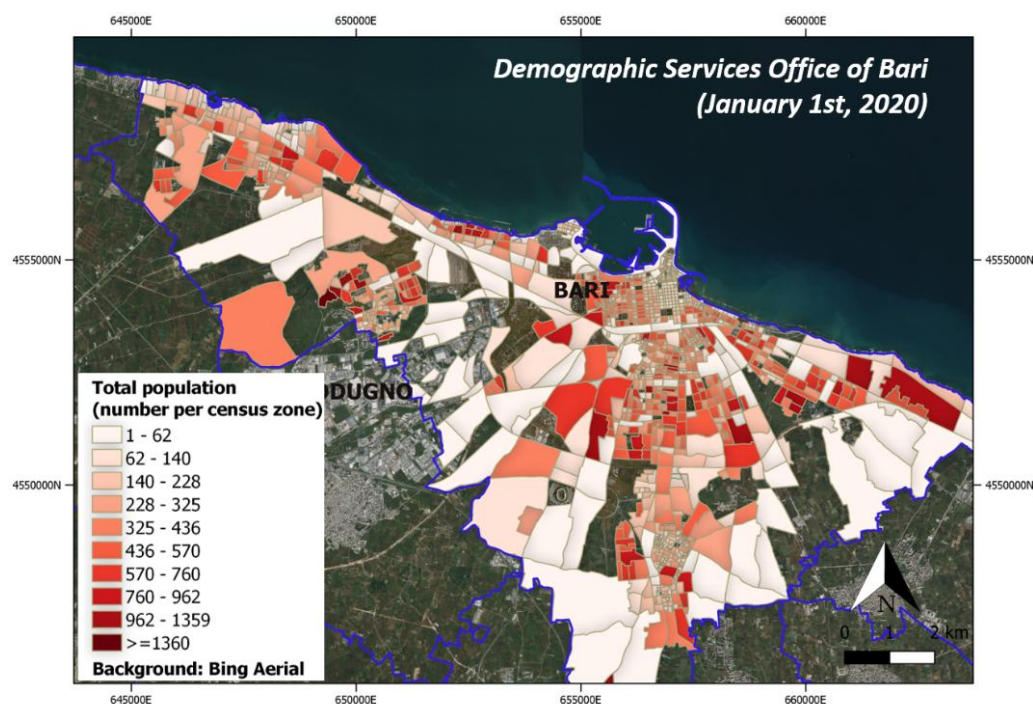


Figure 2-3: Population data provided by Municipality of Bari relevant for 2020.

The method has applied to new data (DSM, DTM and population) for Bari with the aim to obtain updated Total population density maps for 2020 (Figure 2-4) and 2021.



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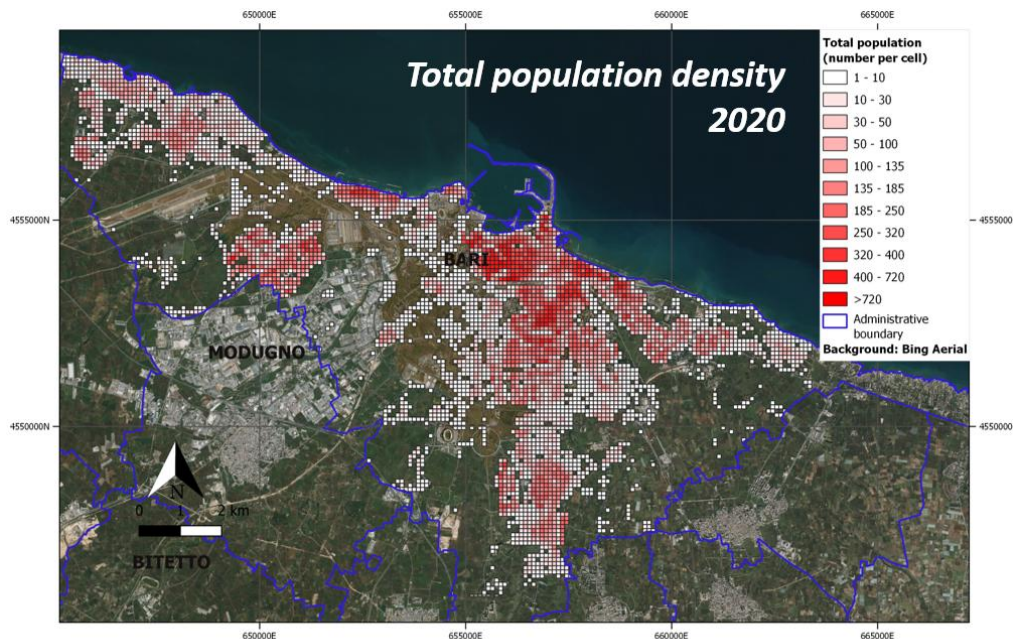


Figure 2-4: Total Population density map for Bari (100x 100 m) generated with 2020 population census data.

2.3 Spatial disaggregation of demographic population groups

In the current release of this document, the same spatial allocation framework was applied to selected ISTAT demographic variables to derive gridded population layers for children, adults and elderly residents. The 2021 population was adopted as the common demographic reference for the 2019–2022 exposure comparison.

To support population-group-specific exposure assessments, the vector-based dasymetric method was applied independently to the 51 resident-population variables included in the P1–P82 group of the 2021 ISTAT census-section extracted from the dataset for Puglia.

The population year 2021 was selected because it corresponds to the most recent official ISTAT population census and falls approximately at the midpoint of the 2019–2022 study period, thus providing a consistent demographic reference for interannual comparisons.

These variables describe the total resident population, males and females, sixteen age groups, and the corresponding sex-by-age groups. Each census count was redistributed to the regular output grid using the same ancillary information and allocation criteria adopted for the total population. The resulting gridded demographic layers provide a consistent basis for examining intra-urban exposure patterns for specific population groups, including children and older residents.

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P1	Popolazione residente - totale	P67	Popolazione residente - femmine - età < 5 anni
P2	Popolazione residente - maschi	P68	Popolazione residente - femmine - età 5 - 9 anni
P3	Popolazione residente - femmine	P69	Popolazione residente - femmine - età 10 - 14 anni
P14	Popolazione residente - età < 5 anni	P70	
P15	Popolazione residente - età 5 - 9 anni	P78	Popolazione residente - femmine - età 55 - 59 anni
P16	Popolazione residente - età 10 - 14 anni	P30	Popolazione residente - maschi - età < 5 anni
P17	Popolazione residente - età 15 - 19 anni	P31	Popolazione residente - maschi - età 5 - 9 anni
P18	Popolazione residente - età 20 - 24 anni	P32	Popolazione residente - maschi - età 10 - 14 anni
P19	Popolazione residente - età 25 - 29 anni	P33	
P20	Popolazione residente - età 30 - 34 anni	P43	Popolazione residente - maschi - età 65 - 69 anni
P21	Popolazione residente - età 35 - 39 anni	P44	Popolazione residente - maschi - età 70 - 74 anni
P22	Popolazione residente - età 40 - 44 anni	P82	Popolazione residente - femmine - età > 74 anni
.....		P83	Popolazione residente - totale di 9 anni e più
P28	Popolazione residente - età 70 - 74 anni	P84	Popolazione residente - maschi di 9 anni e più
P29	Popolazione residente - età > 74 anni	P85	Popolazione residente - femmine di 9 anni e più

Figure 2-5: ISTAT indicators per census zones. **Source:** Italian National Institute of Statistics (ISTAT), Permanent Population and Housing Census 2021 – Data by census section, Puglia Region, file *R16_indicatori_2021_sezioni*, reference date 31 December 2021.

This spatially disaggregated representation supports the identification of areas where elevated PM concentrations coincide with higher densities of vulnerable residents. It also enables more detailed exposure assessments by population group, land-use category and socioeconomic context, as discussed in Section 1.1, “Land-Use and Socioeconomic-Weighted Exposure Model.”

3 PM_{2.5} and PM₁₀ concentration datasets

Once the grid population density map is available for the study area (Section 2), the second step of WP2104 combines it with the high-resolution PM_{2.5} and PM₁₀ concentration maps produced in WP2103. For the Bari study area, annual concentration maps were available for the period 2019–2022, together with the corresponding monthly and seasonal products used for supplementary temporal analyses. Concentrations are expressed in µg/m³. Information on the production and validation of the PM fields is provided in DEL009 and DEL012 and is therefore not repeated in this deliverable.

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4 Common spatial framework

Population and PM products were harmonized in a common projected coordinate reference system and aligned to the same grid origin, extent and cell boundaries.

4.1 Coordinate reference system and analysis domain

All input datasets were transformed, where necessary, to the common projected coordinate reference system ETRS89/UTM zone 33N (EPSG:32633). Grid origin, spatial extent and cell boundaries were aligned to ensure a consistent cell-by-cell integration of population and PM concentration data.

The analysis domain was defined as the largest coherent area for which the PM products and all ancillary datasets required for high-resolution population mapping were jointly available. The resulting common analysis domain includes the central urban area of Bari and the municipality of Modugno, which constitute the main area of interest for the intra-urban exposure assessment. All results presented in this deliverable refer to this common analysis domain.

4.2 Harmonisation on the 300 m grid

The dasymetric population layers, originally generated at 100 m resolution, were aggregated to the common 300 m analysis grid by summing the resident counts of the underlying cells. This procedure preserved the total population represented within the analysis domain. The PM_{2.5} and PM₁₀ concentrations were retained on their original 300 m grid, without spatial interpolation or resampling. Population and concentration rasters were aligned to the same grid origin, extent and cell boundaries before calculating the exposure products.

4.3 Definition of the 900 m output grid

A regular 900 m output grid was adopted for the spatially disaggregated population-weighted indicator. Each 900 m cell corresponds to a block of 3 × 3 cells of the common 300 m grid. The population counts and cell-level exposure contributions were aggregated by sum, without resampling the underlying values. The calculation and normalisation procedures used to derive the local population-weighted mean concentrations are described in Section 3.

4.4 Treatment of zero and NoData cells

Cells located outside the common analysis domain or over the sea were classified as NoData and excluded from the calculations. Cells with valid PM concentrations but no resident population

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contributed neither to the exposure numerator nor to the population denominator; consequently, a population-weighted concentration could not be directly calculated for these cells.

4.5 Summary of input and output grids

Table 4-1 summarises the principal input datasets and derived spatial products used in the Bari population-exposure workflow. Population counts were aggregated by sum to preserve the number of residents, whereas PM concentration values were retained on their original grid without spatial resampling.

Table 4-1. Summary of the input datasets and derived spatial products used in the Bari PM2.5 and PM10 population-exposure assessment.

Component	Native representation	Analysis grid	Unit
Census population	Census sections	100 m	residents
Dasymetric population	100 m	300 m	residents per cell
Demographic groups	100 m	300 m	residents per group
PM2.5 and PM10	300 m	300 m	$\mu\text{g}/\text{m}^3$
Local exposure indicator	—	900 m	$\mu\text{g}/\text{m}^3$
City-scale PWEL	Urban area	City scale	$\mu\text{g}/\text{m}^3$

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5 The Population Weighted Exposure Level (PWEL)

This chapter concerns the SDG 11.6.2 indicator, “Annual mean levels of fine particulate matter (PM_{2.5} and PM₁₀) in cities (population weighted)” [RD 3].

A direct implementation of the SDG 11.6.2 indicator is the Population Weighted Exposure Level (PWEL), computed through the weighted-average formula suggested in the metadata of the SDG 11.6.2 indicator [RD 3]:

$$PWEL_{urb} = (\sum_{i=1}^n C_i * P_{GRID,i}) / P_{urb} \quad (2)$$

where,

- C_i is the PM_{2.5} or PM₁₀ concentration in the generic grid cell i , derived from the high-resolution PM maps produced in WP2103 (DEL07);
- $P_{GRID,i}$ is the population allocated to the same grid cell i , as computed by the CNR-IIA dasymetric method described in Section 2;
- n is the number of grid cells composing the urban district considered;
- P_{urb} is the total population of the urban district considered, i.e. the sum of $P_{GRID,i}$ over all n grid cells.

For this study, population-exposure maps were produced for Bari for the period 2019–2022 by combining the mean PM_{2.5} and PM₁₀ concentration fields with the resident population distribution on a common 300 m grid. For each 300 m grid cell, the pollutant concentration was multiplied by the corresponding number of residents to obtain its contribution to population exposure.

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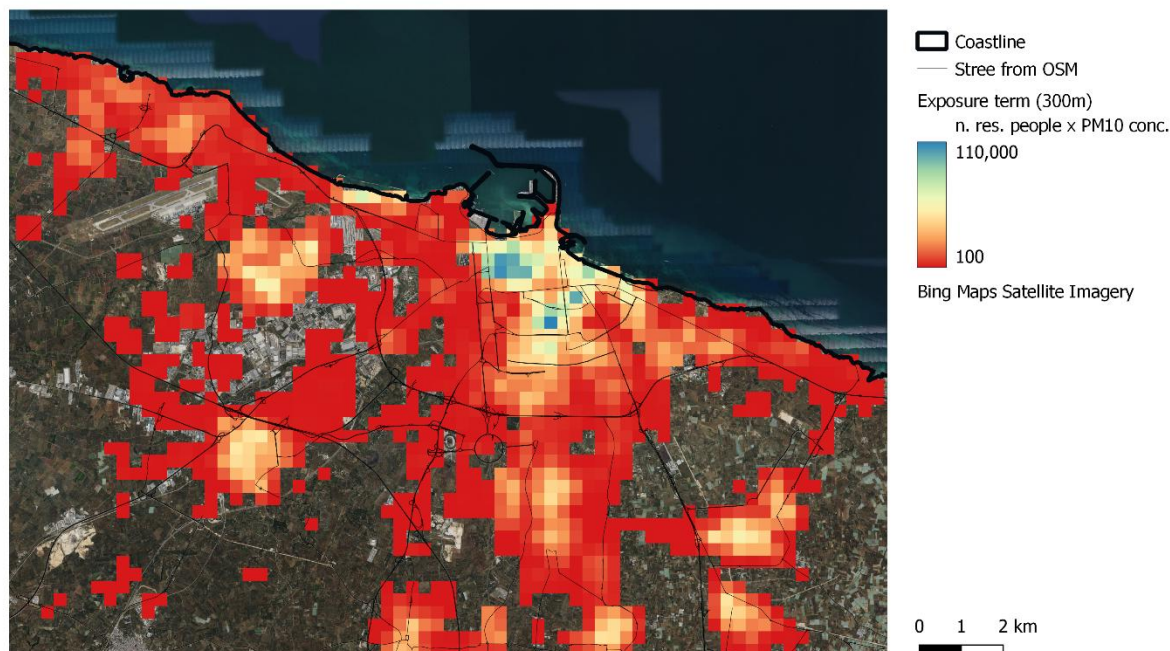


Figure 5-1: Spatial distribution of the PM10 population-exposure contribution in Bari in 2019 at 300 m resolution. Values are expressed in person- $\mu\text{g}/\text{m}^3$.

Then, these contributions were subsequently aggregated to a 900 m grid. For each 900 m cell, the sum of the exposure contributions from the nine underlying 300 m cells was divided by their total resident population. The resulting value represents the population-weighted mean PM concentration within each 900 m cell. This approach provides a spatially disaggregated implementation of SDG indicator 11.6.2 and highlights intra-urban differences in population exposure that would not be apparent from pollutant concentration maps alone.

The PWEL formula was applied to the monthly, seasonal and annual $\text{PM}_{2.5}$ and PM_{10} maps generated in WP2103.

Figures 5-2 and 5-3 show the spatial distribution of the annual cell-level exposure contributions for PM_{10} and $\text{PM}_{2.5}$ in Bari from 2019 to 2022.



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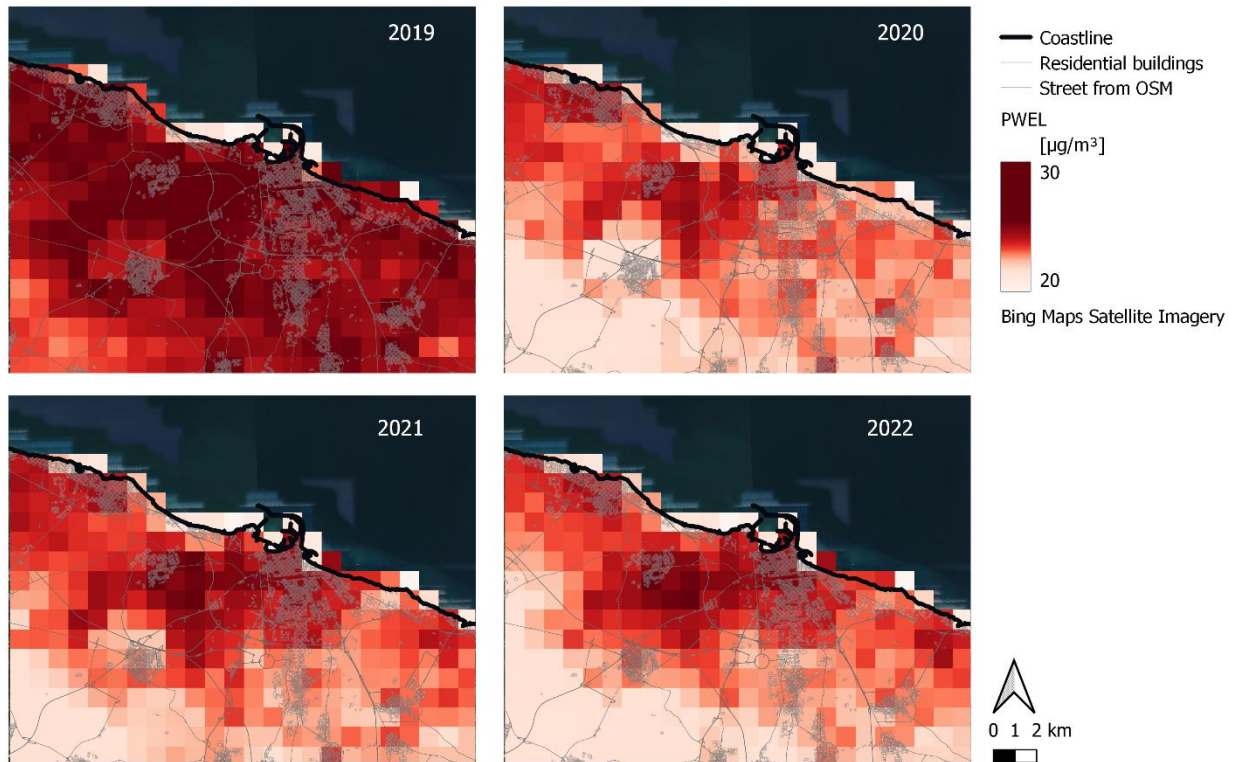


Figure 5-2: Spatial distribution of the annual population-weighted exposure contribution to PM10 in Bari, 2019–2022.

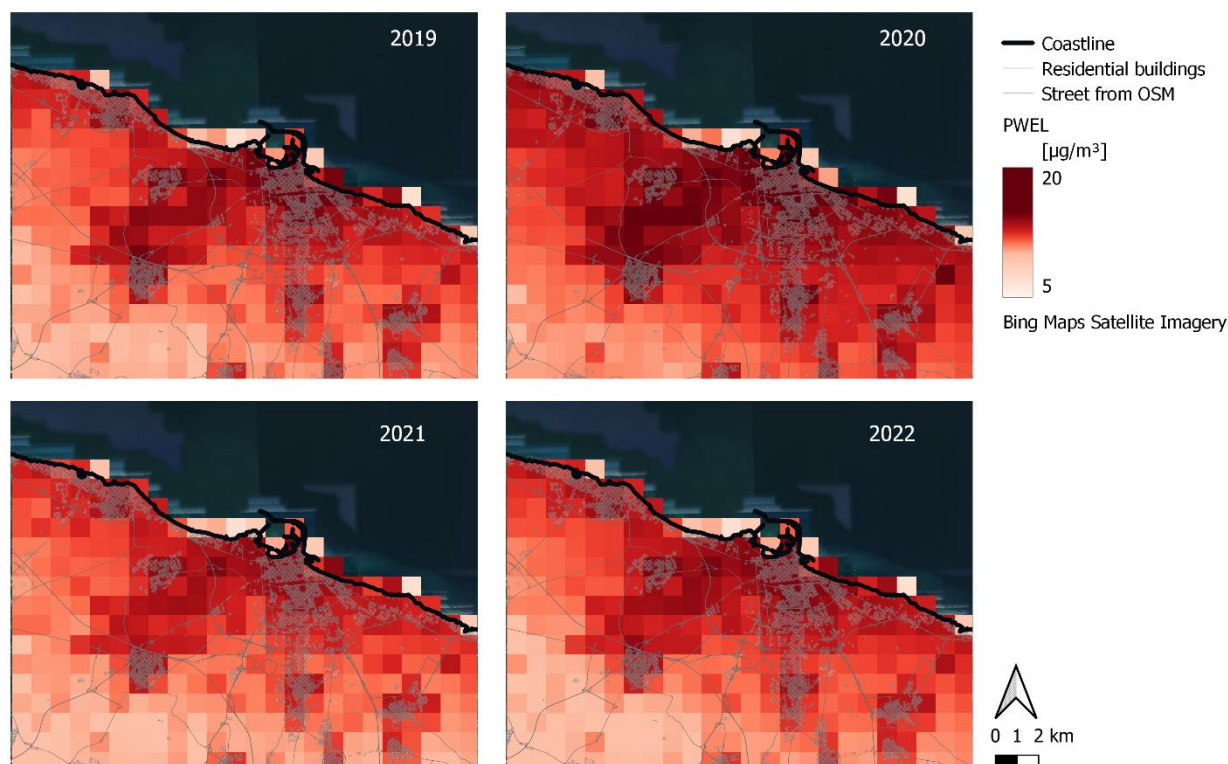


Figure 5-3: Spatial distribution of the annual population-weighted exposure contribution to PM_{2.5} in Bari, 2019–2022.

The seasonal PWEL maps reveal different temporal behaviours for PM_{2.5} and PM₁₀. PM_{2.5} exhibits a comparatively stable spatial pattern throughout the year, with higher population-weighted exposure levels generally concentrated in the more densely urbanised areas. Conversely, PM₁₀ shows more pronounced seasonal changes in both magnitude and spatial distribution. In the representative pre-pandemic year 2019, the summer season is characterised by a widespread increase in exposure levels, whereas during other seasons the highest values are more spatially localised and alternately affect densely populated urban areas and zones associated with industrial or other anthropogenic activities. These variations may reflect the combined influence of seasonal meteorological conditions, regional dust transport, resuspension processes and changes in local emission activity. However, the PWEL maps alone do not allow the respective contributions of these factors to be distinguished, and the observed seasonal patterns therefore warrant further investigation using meteorological, emission and source-apportionment information.



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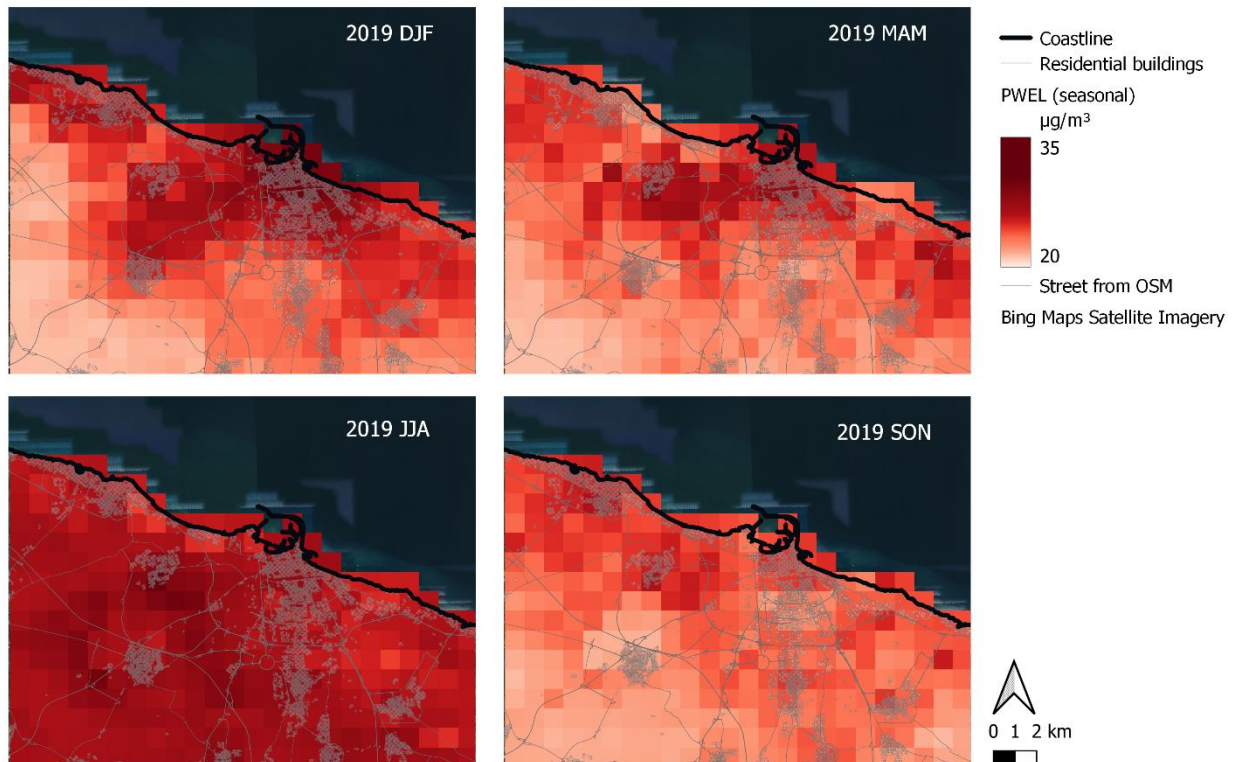


Figure 5-4: Seasonal spatial distribution of the PM10 Population Weighted Exposure Level (PWEL) in Bari in 2019, shown at 900 m resolution using a common colour scale. The panels represent winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

Although the annual values showed relatively limited interannual variability, the spatially disaggregated products highlighted substantial differences within the urban area, reflecting the combined distribution of pollutant concentrations and resident population.

The cell-level contributions can then be aggregated and normalised at the city scale by the total population represented within the study area to derive the annual Population Weighted Exposure Level, consistently with the methodology defined in the UN metadata for SDG indicator 11.6.2 and enabling comparisons of the situation between different cities. It is representative of the chronic exposure of the population and useful for estimates of long-term health effects. To illustrate the effect of population weighting on the resulting city-scale indicator, Table 5-1 compares the annual PWEL values with the corresponding unweighted spatial mean concentrations calculated over the same set of populated *grid cells*.

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Table 5-1: Comparison between unweighted spatial mean concentrations and Population Weighted Exposure Levels in Bari. Values are expressed in $\mu\text{g}/\text{m}^3$. Both metrics were calculated over the same populated 300 m grid cells with valid PM estimates.

Year	PM10 spatial mean	PM10 PWEL	Difference	PM2.5 spatial mean	PM2.5 PWEL	Difference
2019	25.09	25.79	+0.71	12.14	13.74	+1.60
2020	22.81	23.32	+0.51	12.97	14.44	+1.48
2021	23.25	23.83	+0.59	11.87	13.22	+1.35
2022	23.00	23.80	+0.81	12.06	13.50	+1.44

The annual city-wide PWEL values obtained for Bari ranged from 23.32 to 25.79 $\mu\text{g}/\text{m}^3$ for PM10 and from 13.22 to 14.44 $\mu\text{g}/\text{m}^3$ for PM2.5 over the 2019–2022 period.

The Population Weighted Exposure Level was consistently higher than the corresponding unweighted spatial mean for both pollutants. For PM10, population weighting increased the annual values by approximately 0.51–0.81 $\mu\text{g}/\text{m}^3$, corresponding to about 2–4% of the unweighted mean. A more pronounced effect was observed for PM2.5, for which the increase ranged from 1.35 to 1.60 $\mu\text{g}/\text{m}^3$, or approximately 11–13%. These results indicate that higher PM concentrations tend to occur in grid cells containing larger shares of the resident population, particularly in the case of PM2.5. Population weighting therefore provides a different perspective from the spatial mean by giving greater relevance to concentrations occurring where more people live.

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6 Land-Use and Socioeconomic-Weighted Exposure Model

Also, for this second approach, the analysis was carried out in the Bari intra-urban area (Southern Italy) using spatial datasets describing population distribution, land use and particulate matter (PM10, PM2.5) concentrations. The following datasets were integrated within QGIS environment:

1. High-resolution population grids derived from ISTAT data;
2. PM10 and PM2.5 concentration data over the study area;
3. Land use information used to characterize environmental conditions;
4. Administrative and reference cartographic base-layers.

7 Population groups categories

Three population groups were considered: Children (0-15 years); Adults (16-69 years); Elderly population (over 70 years). As in Figure 2.10 the method to risk assessment was based on the vulnerability, exposure, and hazard aspects defined as follows.

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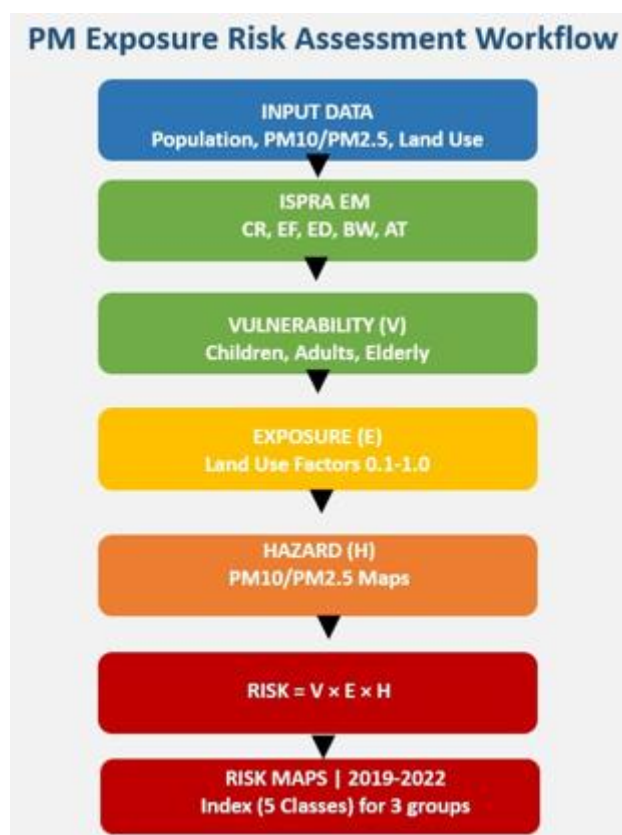


Figure 2.10: Work-flow for PM exposure risk assessment

This is an alternative to the PWEL formula, population exposure to PM can also be estimated by adapting the classical chronic daily intake model used in environmental risk assessment for contaminated sites (APAT, 2008; Ispra 2025), expressed as

$$EM = (CR \times EF \times ED) / (BW \times AT),$$

where CR is the contact rate, EF the exposure frequency, ED the exposure duration, BW the body weight and AT the averaging time. All parameters represent EM: the intrinsic vulnerability of people, based on literature data (Table 2.3).

Table 7-1 - The calculated EM coefficients for different population groups

Population group	EM
Children	0.60 m ³ /Kg day
Adults	0.28 m ³ /Kg day
Elderly people	0.21 m ³ /Kg day

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Higher EM values indicate greater vulnerability to airborne particulate matter exposure where:

Children > Adults > Elderly

The reasons are: i) children have lower body weight but a higher metabolic rate; ii) children inhale a relatively large amount of air in proportion to their body weight; iii) elderly generally have lower respiratory rates and activity levels, resulting in reduced exposure per kilogram of body weight.

These aspects are widely documented in the exposure factor databases used by the JRC (2025), US EPA (2021), WHO (2021), as in environmental risk assessment methodologies. Population data were initially available at a finer spatial resolution than the air-quality grid. To obtain a common spatial framework, vulnerability values were spatially aggregated to the PM grid through GIS-based zonal statistics procedures. For each PM cell, the mean vulnerability value of all underlying population cells was calculated, generating vulnerability maps for children, adults, and elderly populations.

7.1 Land Use Factor

Land use categories were converted into different classes according to their potential influence on human exposure. Each land-use class was assigned a specific weighting factor (0,1 to 1) representing the intrinsic vulnerability condition associated with environment (Table 2.4). The resulting coefficients were spatially aggregated to the PM grid, producing a new layer.

Table 7-2 - Land use classes and weight assigned for vulnerability evaluation

Land use	Weight
Industrial, commercial, other roads	1
Rural	0.4
Residential	0.2
Other	0.1

The “Industrial, commercial, and road” areas (weight = 1.0) represent the highest potential for vulnerability, as they are characterized by industrial and commercial activities and heavy vehicular

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traffic, the primary sources of atmospheric particulate matter emissions. For this reason, the maximum value has been assigned.

The “Rural” areas (weight = 0.4) generally experience lower anthropogenic pressure and a lower density of emission sources compared to urbanized areas. However, they can be affected by emissions from agricultural practices and the transport of pollutants from neighboring areas. In this case, an intermediate weight has been assigned.

The “Residential” areas (weight = 0.2) are associated with lower exposure levels than industrial and commercial zones. Although they house the exposed population, the direct presence of emission sources is generally more limited, justifying a relatively low weight.

The “Other” land uses (weight = 0.1) include all areas that do not fall into the previous classes (e.g., natural areas, open spaces, undeveloped land). Such areas are considered to make a low contribution to exposure and are therefore assigned to the minimum weight.

7.2 PM10 and P2.5 Hazard Assessment

PM10 and PM2.5 concentrations recorded in the period 2019-2022 were linked to the analysis grid to represent the environmental hazard component. Average PM concentrations were assigned to each grid cell, generating the hazard map of the study area. Since hazard is defined as the probability of a phenomenon of a specific intensity occurring in a particular area within a given timeframe, PM raster images were considered key elements in defining this aspect. Indeed, the PM rasters covering the four-year observation period recorded information such as the phenomenon's intensity and its spatial and temporal extent.

7.3 Exposure

The exposure component was calculated by spatially integrating land-use information and atmospheric particulate matter (PM) concentrations with population vulnerability data for children, adults, and the elderly people. Cells with no resident population were assigned an exposure value of zero, while populated cells were assigned a coefficient based on the adopted ISPRA approach. Subsequently, land-use classes were reclassified into exposure-related weights, reflecting the potential influence of different urban and environmental settings on human exposure. PM concentration data were then spatially linked to each grid cell through spatial analysis, allowing each cell to be characterized by a representative PM value. The final exposure

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index was calculated by combining the vulnerability indicator, the land-use weighting factor, and the PM concentration using a multiplicative approach.

7.4 Risk Calculation

The final risk assessment was based on the integration of vulnerability, hazard, and exposure components. For each grid cell, risk was computed as:

$$\text{Risk} = \text{Vulnerability} \times \text{Exposure} \times \text{PM}$$

This operation was performed separately for children, adults, and elderly populations, producing independent risk maps for PM10 and PM2.5 for 2019-2022 years. The Risk index has been subdivided into 5 classes with a color scale ranging from blue to red (1: very low risk; 2: low risk; 3: moderate risk; 4: high risk; 5: very high risk).

7.5 Output Maps

7.5.1 PM2.5

The children risk maps show generally low risk values across the study area, with only a limited number of cells reaching moderate risk classes between 2019 and 2021. In 2022, risk values decrease markedly, with almost the entire area falling within the lowest risk class (Figure 2.11). Adults exhibit the highest PM2.5 risk levels among the analysed population groups. Moderate and high-risk classes are concentrated in specific urban sectors and remain visible throughout the entire study period, indicating persistent exposure conditions (Figure 2.12). The elderly population presents intermediate PM2.5 risk levels, generally lower than adults and only locally reaching moderate classes. A slight reduction in risk can be observed in the last years of the study period (Figure 2.13).



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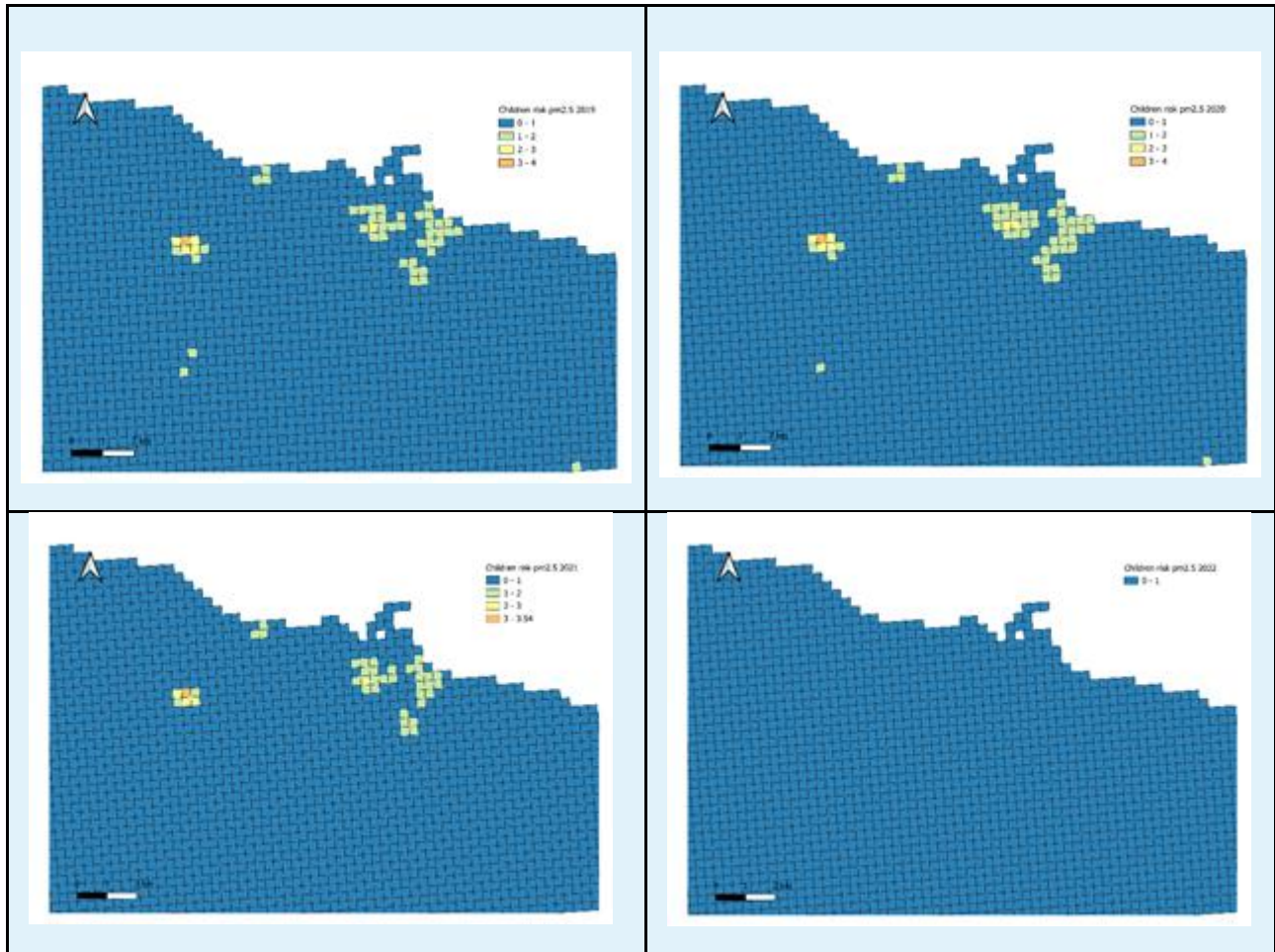


Figure 7-1 - Figure 7 1 - Chidren Risk distribution to MP2.5 exposure (2019-2020-2021-2022). See the text for the class definition.



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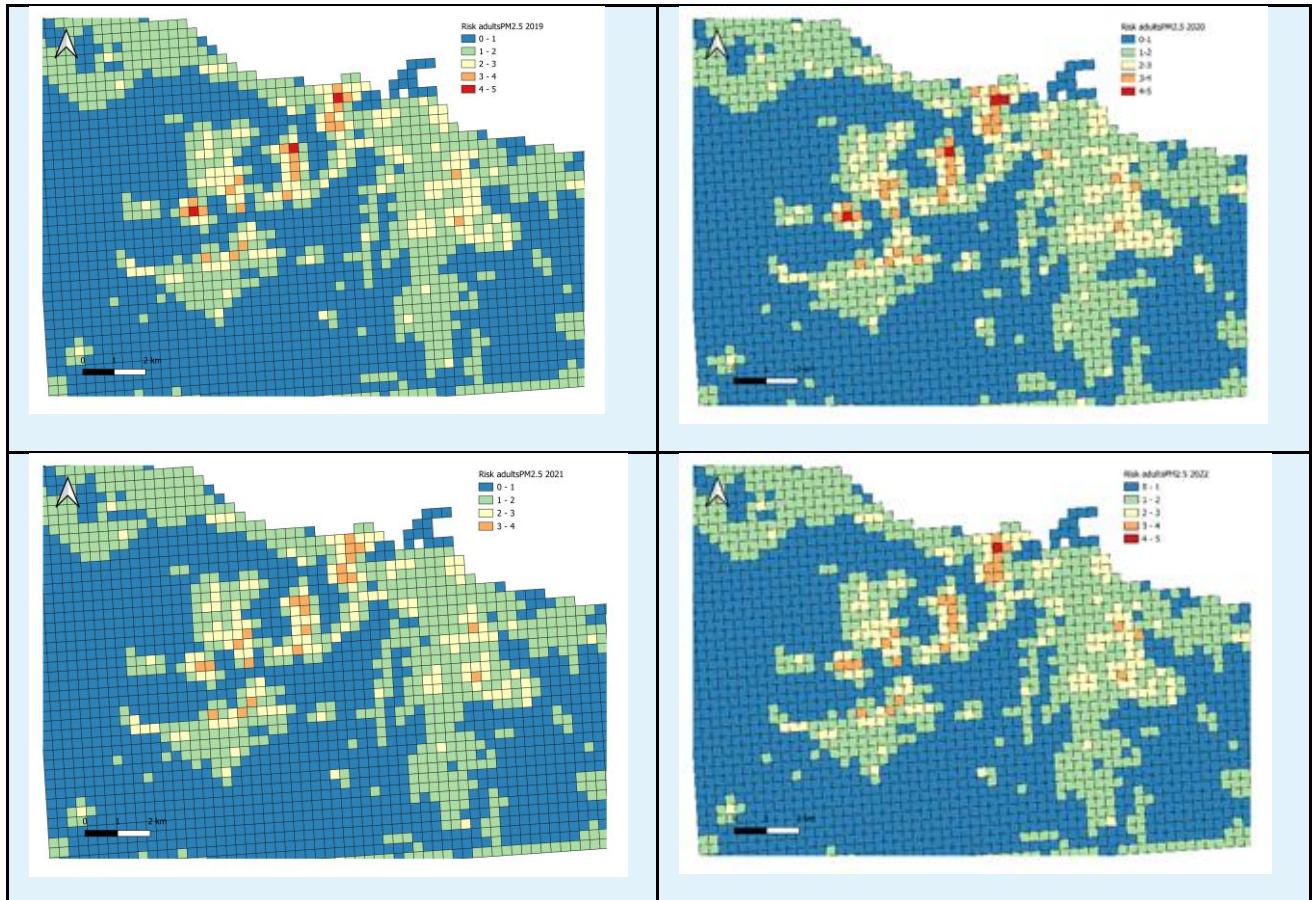


Figure 7-2 - Adults Risk distribution to MP2.5 exposure (2019-2020-2021-2022)



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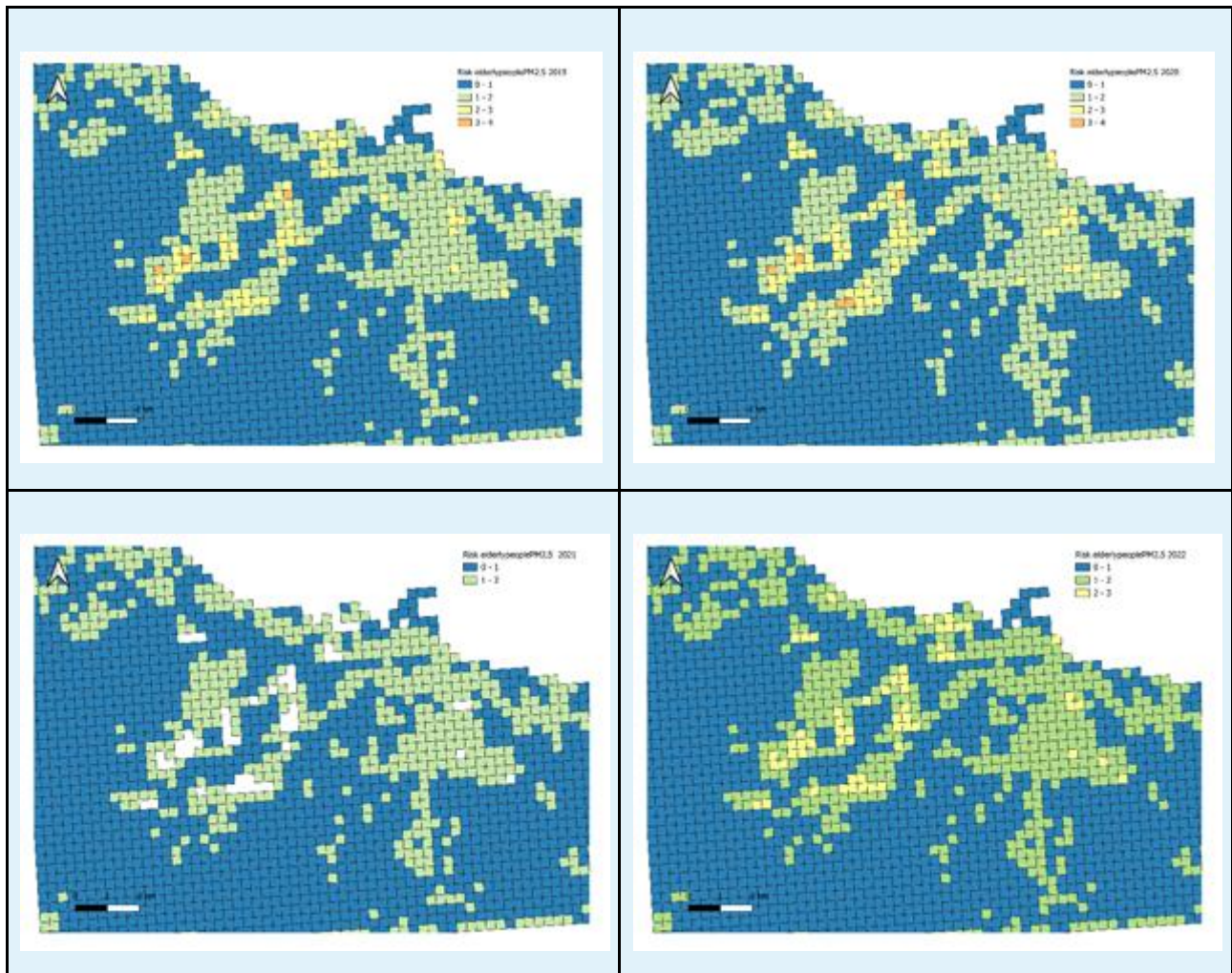


Figure 7-3 - Elderly people Risk distribution to PM2.5 exposure (2019-2020-2021-2022)

7.6 PM10

PM10-related risk for children is generally limited and confined to a few localized hotspots that persist through the study period. Most cells remain within the lowest risk classes (Figure 7-4).

Adults display the most extensive spatial distribution of PM10 risk. Moderate and high-risk classes are widespread in urbanized sectors, confirming this category as the most exposed according to the adopted methodology (Figure 7-5).

The elderly group shows a spatial pattern like that observed for adults, although with lower overall risk intensity. Moderate-risk areas are mainly concentrated in the central and eastern sectors of the study area (Figure 7-6).



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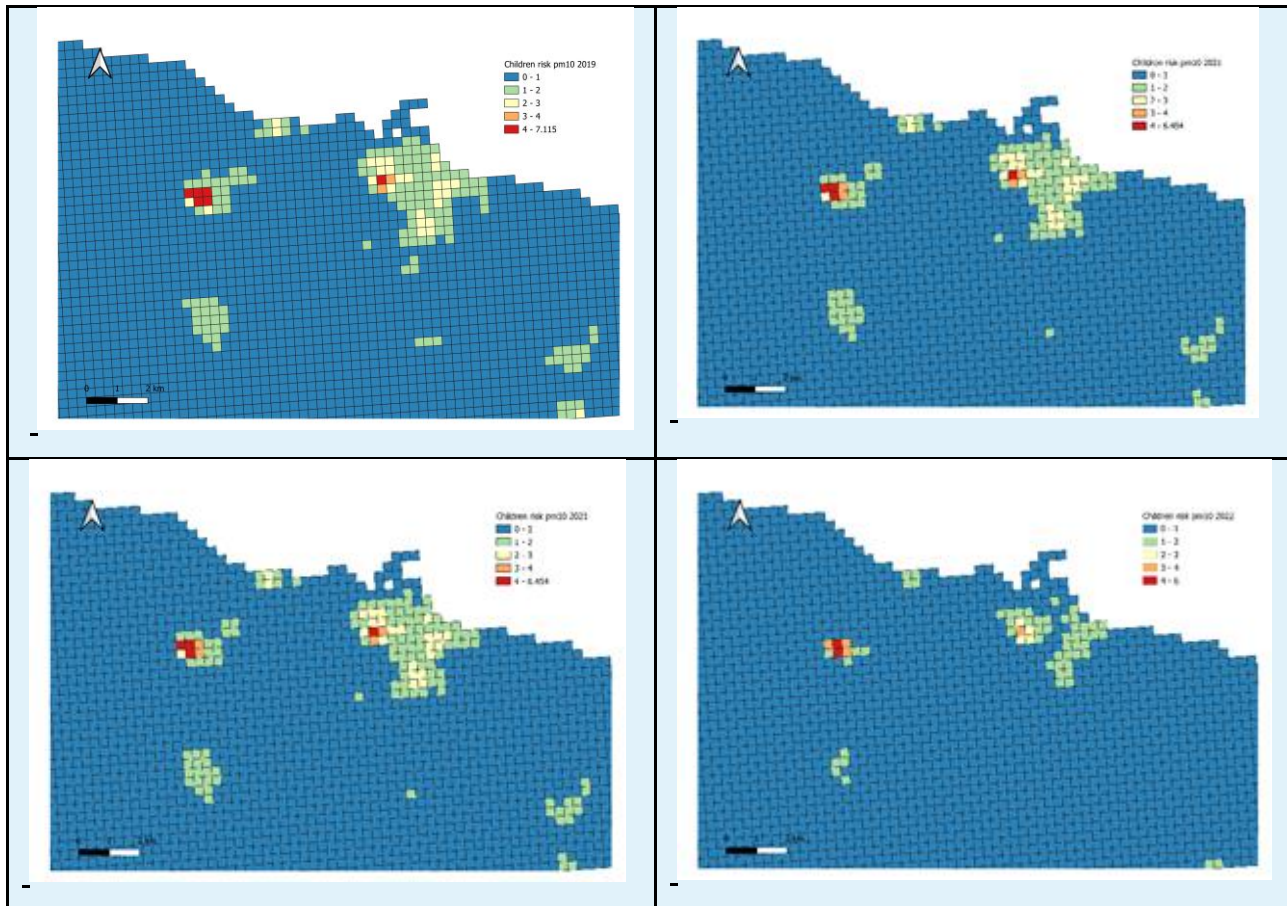


Figure 7-4 - Children Risk distribution to PM10 exposure (2019-2020-2021-2022). See the text for the class definition.



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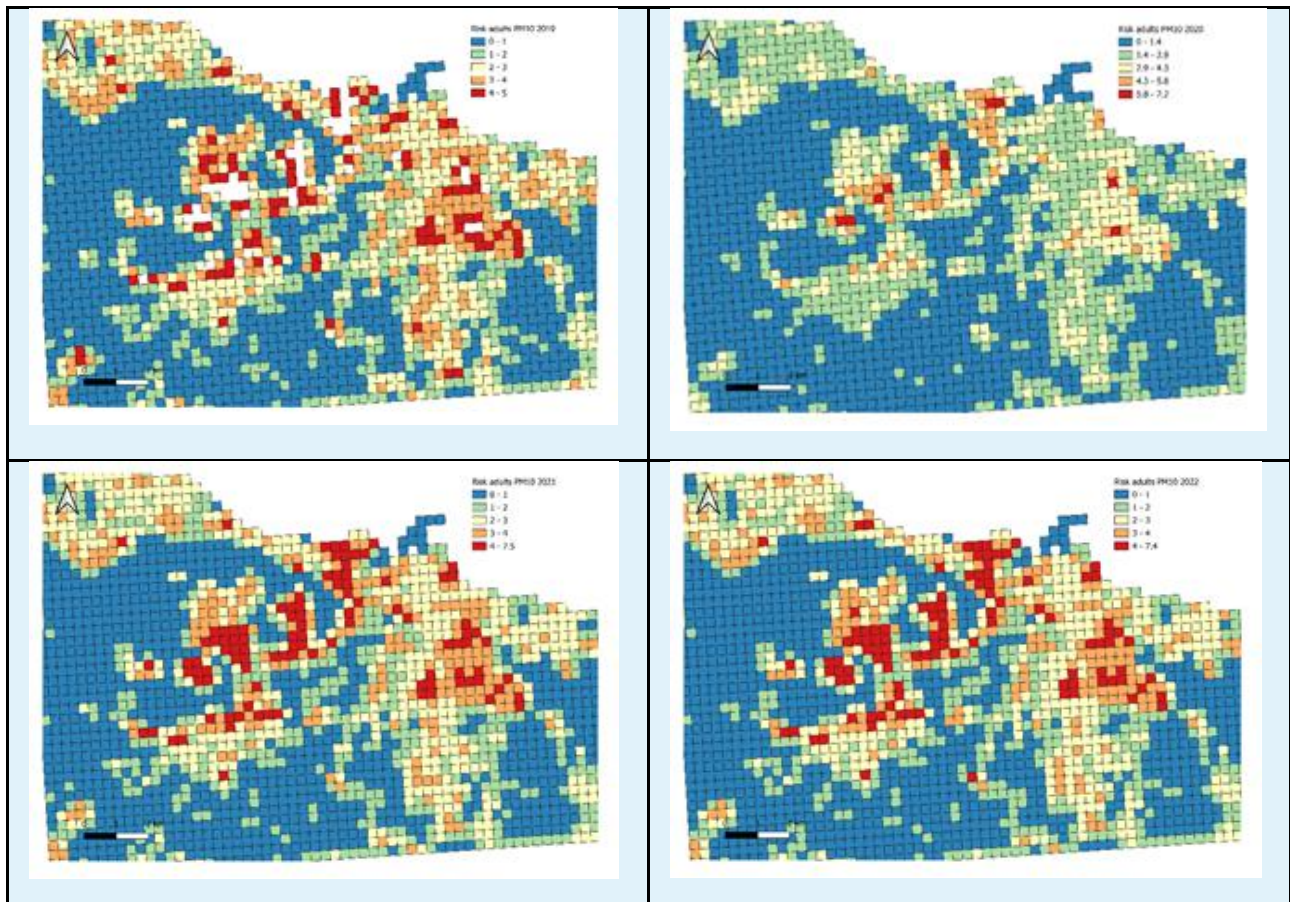


Figure 7-5 - Adults Risk distribution to MP10 exposure (2019-2020-2021-2022). See the text for the class definition.



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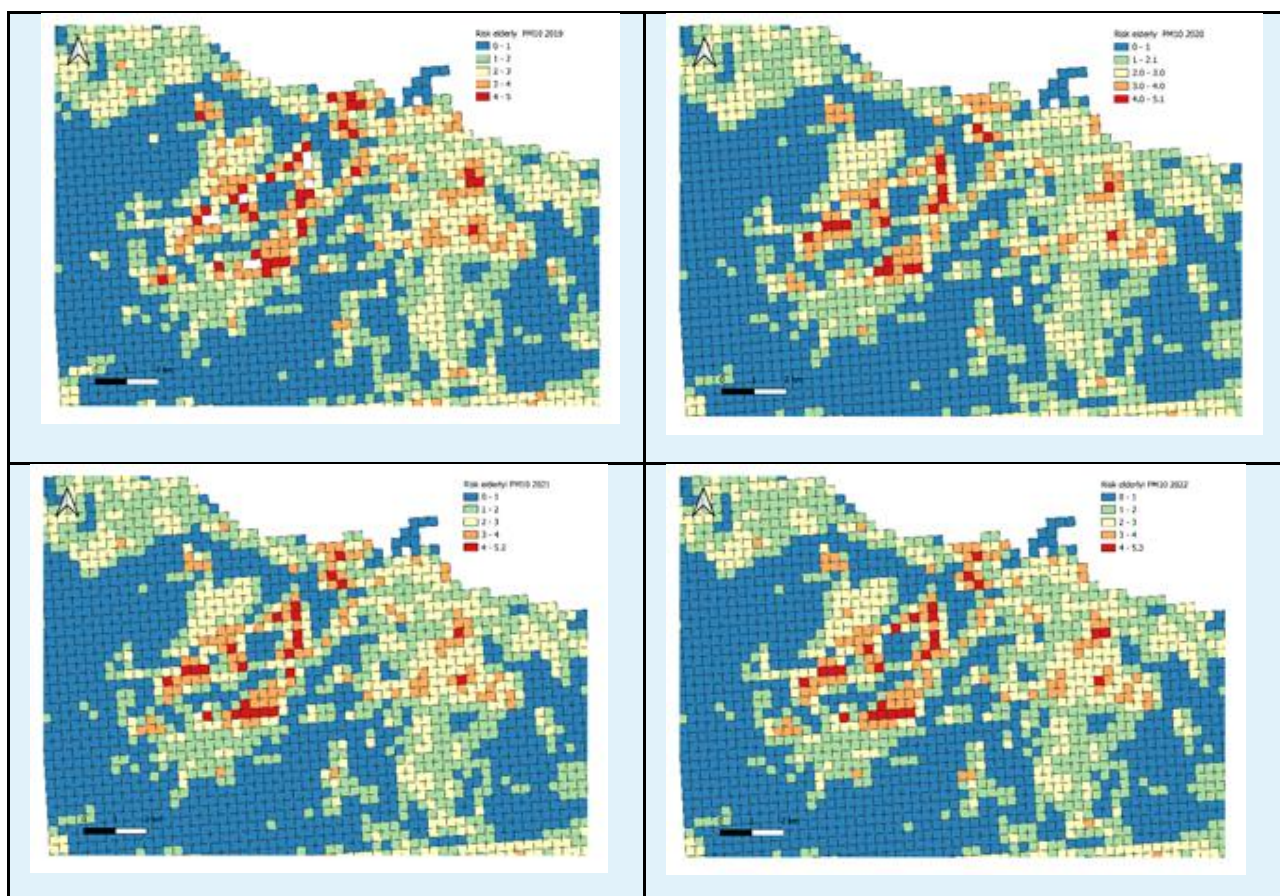


Figure 7-6 - Elderly people Risk distribution to MP10 exposure (2019-2020-2021-2022). See the text for the class definition.

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8 WHO-based Warning Area Identification

To support the identification of warning areas, understood here as urban areas requiring particular attention, the 2021 WHO Global Air Quality Guidelines were adopted as a health-based reference framework. In addition to the recommended Air Quality Guideline (AQG) levels, the WHO defines four interim targets representing progressively more stringent air-quality benchmarks and supporting incremental emission-reduction strategies towards the achievement of the AQG levels.

Table 8-1: Interim level target. Source: [WHO Global Air Quality Guidelines 2021](#).

Pollutant	IT-1	IT-2	IT-3	IT-4	AQG
PM2.5	35	25	15	10	5
PM10	70	50	30	20	15

For the purposes of this study, each annual concentration and Population Weighted Exposure Level was assigned to an interim-target class according to the most stringent WHO target achieved. This classification makes it possible to evaluate not only whether concentrations comply with legally binding limits, but also how far they remain from the health-based AQG levels. Warning areas can consequently be identified as grid cells falling within the less favourable interim-target classes, particularly where the class assigned to the PWEL is less favourable than that assigned to the corresponding unweighted mapped concentration. Such differences indicate areas where the spatial distribution of the resident population increases the relevance of exposure and where further investigation or targeted mitigation measures may be warranted.

Table 8-2: WHO-based attention levels adopted in this study for the identification of warning areas. Attention increases from level 1 to level 6. Each level indicates the most stringent WHO annual benchmark achieved for PM2.5 and PM10.

WHO-based attention level	PM2.5 annual range	PM10 annual range	Interpretation
1	≤ 5	≤ 15	AQG level achieved
2	> 5 to ≤ 10	> 15 to ≤ 20	Between AQG and IT-4
3	> 10 to ≤ 15	> 20 to ≤ 30	IT-3 achieved; IT-4 not achieved
4	> 15 to ≤ 25	> 30 to ≤ 50	IT-2 achieved; IT-3 not achieved
5	> 25 to ≤ 35	> 50 to ≤ 70	IT-1 achieved; IT-2 not achieved
6	> 35	> 70	IT-1 not achieved

The procedure was applied consistently to both pollutants and to all annual products for the 2019–2022 period. The complete set of WHO-based attention-area maps was provided within release

SW008. Figure 8-1 is included as an illustrative example of the procedure, showing the annual PM_{2.5} local population-weighted concentration for Bari in 2020 at 900 m resolution.

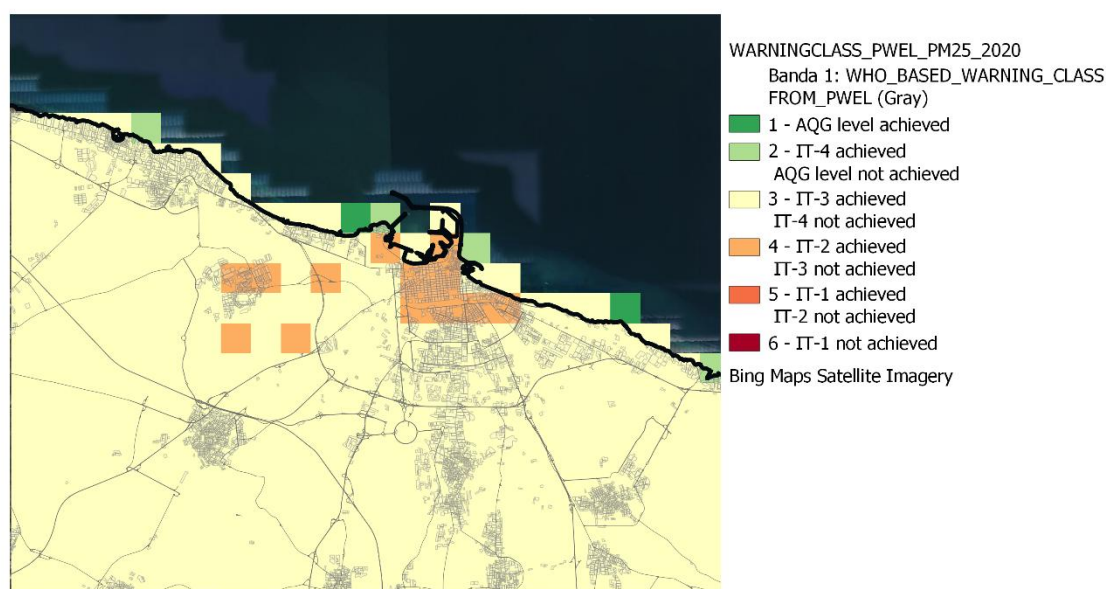


Figure 8-1: WHO-based attention levels derived from the annual PM_{2.5} PWEL in Bari for 2020 at 900 m resolution.

Although the annual PM₁₀ and PM_{2.5} values estimated for Bari (subsection 5) remained below the annual limit values currently applied in Italy, both the unweighted concentrations and the population-weighted exposure levels exceeded the corresponding WHO AQG levels.

The city-scale PWEL values—13.22–14.44 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 23.32–25.79 $\mu\text{g}/\text{m}^3$ for PM₁₀—met WHO Interim Target 3 but did not meet the more stringent Interim Target 4. The spatial classification nevertheless revealed intra-urban variability, with some grid cells falling within either more or less favourable benchmark classes than the city-scale value. At city scale, population weighting consistently increased the estimated exposure compared with the corresponding unweighted spatial mean, indicating that relatively higher concentrations tended to occur in grid cells containing larger shares of the resident population.

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9 Validation and Quality Control

Validation and quality control were conducted at three levels: the input PM concentration products, the dasymetric population layers, and the spatial integration procedures used to derive the population-exposure products.

The PM_{2.5} and PM₁₀ concentration fields were evaluated within the APEMAIA validation framework against available ground-based observations and the modelling products provided by ARPA Puglia. The methods and results of the PM validation are documented in DEL012 and are therefore not repeated in this deliverable [AD 5].

The validation of the high-resolution population component was initially conducted as part of the activities documented in the preliminary version of DEL010. Quality control included verification that the population allocated to the output grid was consistent with the source census totals, that no population was lost during the dasymetric redistribution, and that the resulting spatial patterns were plausible in relation to the distribution and use of buildings.

The CNR-IIA dasymetric method was independently validated using the municipal population dataset updated to 2020. The validation procedure and its results are documented in the preliminary version of DEL010 and are not repeated in full in the present deliverable. The final exposure assessment uses the demographic variables provided by the 2021 ISTAT Census. At municipal scale, the total resident population of Bari remained broadly stable between 2019 and 2021, increasing approximately +0.2%. The 2021 demographic dataset was therefore adopted as a consistent reference for the comparison of exposure estimates over the 2019–2022 period. Additional mass-preservation checks were performed to verify the internal consistency of the redistribution procedure, as reported in the preliminary delivery of this document.

Specific quality-control procedures were subsequently applied to the population-exposure workflow developed in the final release. These included:

- verification of the common coordinate reference system and analysis domain;
- alignment of the population and PM rasters to the same 300 m grid origin, extent and cell boundaries;
- confirmation that aggregation from 100 m to 300 m preserved the represented population;
- verification that every 900 m output cell corresponded to the appropriate underlying 3 × 3 block of 300 m cells;
- independent checks of the aggregated population and exposure-contribution sums;
- exclusion of cells outside the common analysis domain and over the sea;

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- separate treatment of zero-population cells and NoData values.

The reliability of the resulting exposure products depends on the quality, temporal representativeness and spatial resolution of both input components. The dasymetric population grids remain model-based estimates of residential distribution, while the PM products represent ambient concentrations rather than individual exposure. These limitations were taken into account when interpreting the spatial patterns and the differences among years and population groups.

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10 Conclusions

The final DEL010 implements the population-exposure component of WP2104 by integrating the high-resolution PM_{2.5} and PM₁₀ products with the dasymetric distribution of the resident population. The workflow produces cell-level exposure contributions at 300 m resolution, local population-weighted mean concentrations at 900 m resolution, and city-scale Population Weighted Exposure Levels for the common Bari and surrounding municipalities' analysis domain.

For the 2019–2022 period, the city-scale PWEL ranged from 23.32 to 25.79 µg/m³ for PM₁₀ and from 13.22 to 14.44 µg/m³ for PM_{2.5}. Population-weighted values were consistently higher than the corresponding unweighted spatial means, particularly for PM_{2.5}. The 900 m products further revealed intra-urban differences that are not represented by a single city-scale indicator. The WHO-based attention classes provide an additional health-based framework for interpreting these spatial patterns.

The complementary maps (subsection 7.5) should be interpreted as relative decision-support screening products. They combine the distribution of demographic groups, PM concentrations and urban or land-use characteristics, but do not represent a directly measurable physical quantity, individual pollutant dose, probability of adverse effects or absolute health risk. The higher and more widespread scores observed for adults mainly reflect the spatial distribution and size of the population group, together with the assumptions and weights adopted in the screening framework.

Differences observed in 2020 are reported descriptively. The present analysis does not allow the respective effects of COVID-19 restrictions, meteorological conditions, secondary aerosol formation, domestic heating and regional transport to be separated. A causal interpretation of the 2020 patterns would require a dedicated analysis using emission, meteorological and source-apportionment information.

The priority attention classes and associated warming areas are intended to support expert interpretation and decision-making. There are susceptible to be refined by domain experts according to local knowledge, monitoring evidence and planning objectives. The maps may therefore support prioritisation of monitoring, field investigation and mitigation actions.

Further limitations concern the temporal representativeness of census population data, the uncertainty inherent in dasymetric population allocation, the resolution and accuracy of the PM products, and the simplified assumptions used in the complementary screening analysis. E.g., the overall demographic consistency of the reference population does not account for short-term population mobility or possible local changes in the within-city distribution of residents. Future work

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may strengthen the assessment through sensitivity analysis of the screening weights, updated demographic data, mobility information, epidemiological evidence and locally validated health-related indicators.