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Transboundary Storm Risk and Impact Assessment in Alpine Regions

IDENTIFICATION AND CHARACTERIZATION OF EXPOSED ASSETS AND THEIR VULNERABILITY TO STORMS

Deliverable 4.3

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1 INTRODUCTION

The purpose of this document is to describe the design and development of an exposure model compatible with multiple natural hazards and different vulnerability approaches, to be employed in cross-border risk assessment applications. In the next chapter the main approach and methodology are described while in the subsequent section the implementation of a preliminary model within the framework of TRANS-ALP project is provided and discussed. In the conclusions several concluding remarks are given.

2 THE METHODOLOGY

In this section the main conceptual framework for exposure modelling is provided, and the specific approach followed in the project is described and discussed.

2.1 CONCEPTUALIZATION

Exposure is a fundamental concept and component of the wider risk assessment framework. Before going into details, we follow, as reference, the formulation of risk (see Figure 1) provided by IPCC in its latest version, which is also largely compatible with the one proposed by UNDRR in the 2015-2030 Sendai framework of disaster risk reduction (e.g., see the UNDRR´s terminology of DRR).

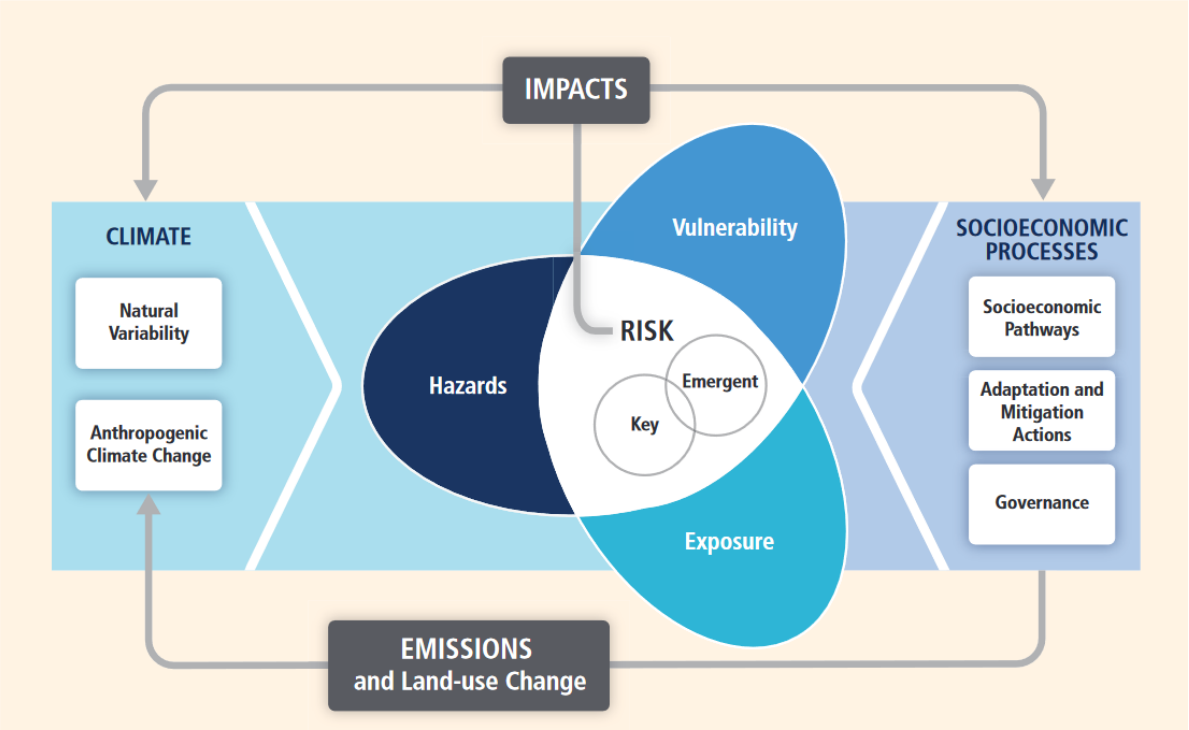

Figure 1 — Representation of risk-related components in the AR5 framework (source: IPCC AR5)

The basic concepts underlying are briefly recalled in the following:

- **Hazard**. A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. *Annotations*: Hazards may be natural, anthropogenic or socio-natural in origin. Natural hazards are predominantly associated with natural processes and phenomena. Anthropogenic hazards, or human-induced hazards, are induced entirely or

predominantly by human activities and choices. This term does not include the occurrence or risk of armed conflicts and other situations of social instability or tension which are subject to international humanitarian law and national legislation. Several hazards are socio-natural, in that they are associated with a combination of natural and anthropogenic factors, including environmental degradation and climate change. Hazards may be single, sequential or combined in their origin and effects. Each hazard is characterized by its location, intensity or magnitude, frequency and probability. Biological hazards are also defined by their infectiousness or toxicity, or other characteristics of the pathogen such as dose-response, incubation period, case fatality rate and estimation of the pathogen for transmission (UNDRR).

- **Exposure**. Describes the extent to which sensitive assets and systems are exposed to hazardous conditions (that is, conditions that can potentially generate impacts). **Exposed elements** are physical, socio-economic or intangible assets or systems that are susceptible to be impacted (and potentially damaged) by one or more hazardous conditions and hence can incur a loss.

- **Vulnerability.** The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (UNDRR). Vulnerability can be also described in terms of two different type of factors, namely sensitivity and coping capacity:

    - **Sensitivity**. Sensitivity determines the degree to which a system is adversely or beneficially affected by a given climate change exposure. Sensitivity is typically shaped by natural and/or physical attributes of the system including topography, the capacity of different soil types to resist erosion, land cover type. But it also refers to human activities which affect the physical constitution of a system, such as tillage systems, water management, resource depletion and population pressure. As most systems have been adapted to the current climate (e.g. construction of dams and dikes, irrigation systems), sensitivity already includes historic and recent adaptation. Societal factors such as population density should only be regarded as sensitivities if they contribute directly to a specific climate (change) impact.

    - **Coping Capacity**. The ability of people, organizations and systems, using available skills and resources, to manage adverse conditions, risk or disasters. The capacity to cope requires continuing awareness, resources and good management, both in normal times as well as during disasters or adverse conditions. Coping capacities contribute to the reduction of disaster risks (UNDRR).

- **Potential Impacts**. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts. Climate change impacts can form a chain from more direct / physical impacts (e.g., erosion) to indirect impacts (e.g., reduction in yield, loss of income) which stretches from the biophysical sphere to the societal sphere. In many developing countries, direct dependency on natural resources means that the link between biophysical impacts of climate change and human activities and well-being is particularly strong (see Figure 2).

- **Stressors (conditioning factors)**. Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate-related risk. Conditioning factors refer to environmental conditions that can exacerbate the impacts and increase the risk by, e.g., increasing the sensitivity of the exposed assets, or by affecting negatively the copying capacity of the affected communities.

- **Risk**. The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk = (Probability of Events or Trends) × Consequences. Risk results from the interaction of vulnerability, exposure, and hazard (see Figure 1). In this report, the term risk is used primarily to refer to the risks of climate-change impacts.

It is therefore clear how important is the exposure component, and how tightly is it connected to the modelling of vulnerability.
We also note that the boundary between exposure and vulnerability sometimes fades since information about exposure would imply for instance the knowledge about what (and how many) vulnerable assets are present in a given area, while their detailed description would also carry out information on their sensitivity with respect to one or more natural hazards.

To give a specific example, exposure to most natural hazards would include the distribution of resident or commuting population (how many people can be found in average in a given area), while the demography of this population (e.g., the share of elderly people or children under 5) would bring vulnerability related information (elderly people and children would be for instance more vulnerable to heat waves). The TRANS-ALP approach focuses therefore on considering exposure information also a supporting /complementing component for vulnerability assessment, and as such aims at providing as much information as possible on the vulnerable assets, independently on prior knowledge on the spatial distribution of hazard.
Although this implies the assumption that hazards can potentially threaten exposed assets independently on their geographical location (which is not the case considering, e.g., most mass wasting phenomena that are usually confined to areas close to slopes) such assumption would make the modelling of exposure and vulnerability more straightforward and independent, and would have no negative impact on the risk assessment, since the only drawback would be the potential increase in complexity and size of the model. This complexity is anyway increasing when considering multiple, possibly concurring natural hazards which have different spatial footprint and temporal dynamics.

2.2 THE METHODOLOGY

In a multi-hazard risk assessment framework we aim at an exposure model compatible with the set of targeted hazards (but largely independent from their spatial footprint) and where the considered assets are described at the level of detail most compatible with the subsequent vulnerability modelling. The design and implementation methodology entails several tasks:

1. Screening for impacting mechanisms,
2. highlighting main exposed assets and systems and
3. considering explicitly their vulnerability-related features
4. defining spatial resolution and aggregation,

These tasks will be further described in the following. The analysis is based on the impact chains developed within the project to describe the impacting mechanisms of intense storms, shown in Figure 2 and Figure 3. In each impact chain the factors related to the different components (hazard, exposure, vulnerability and impacts) are grouped together and color-coded accordingly, while causal links have been explicitly indicated only for intermediate impacts. Links related to exposure and vulnerability are not indicated but related information is provided in the narrative description of the impacts themselves. In grey a few external drivers (i.e., conditioning factors) are indicated as well.

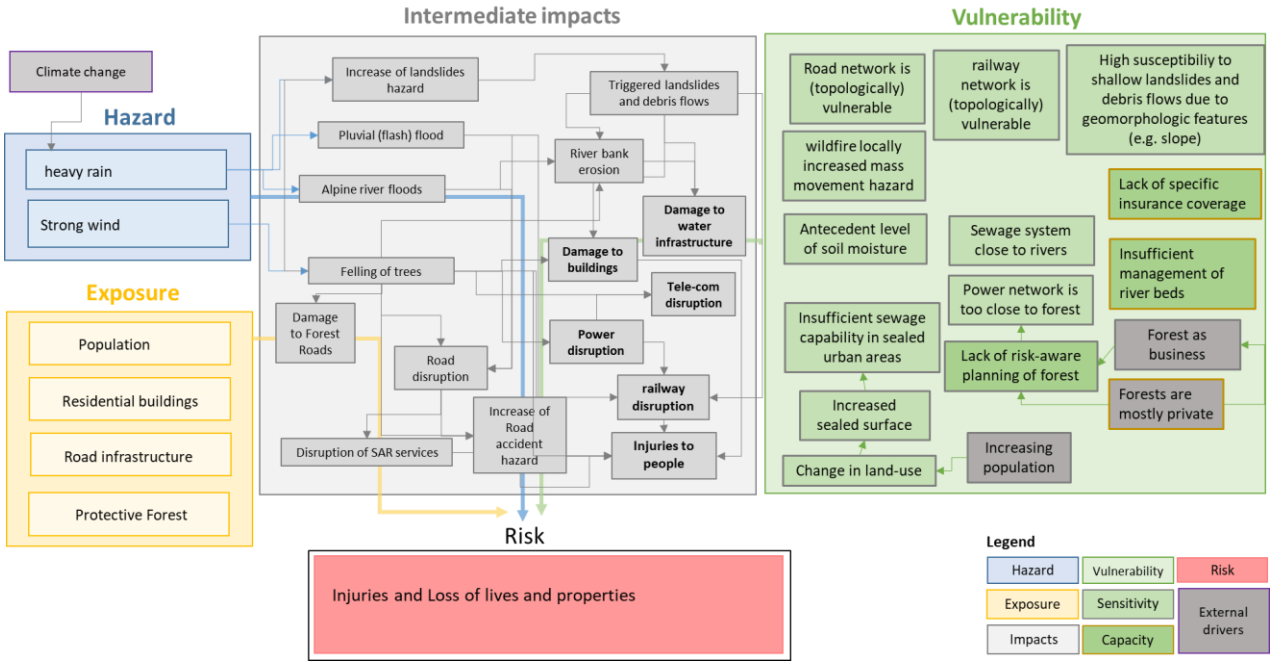

Figure 2 — Event Storm "VAIA" - Impact chains related to target risk: "Injuries and loss of lives and properties"

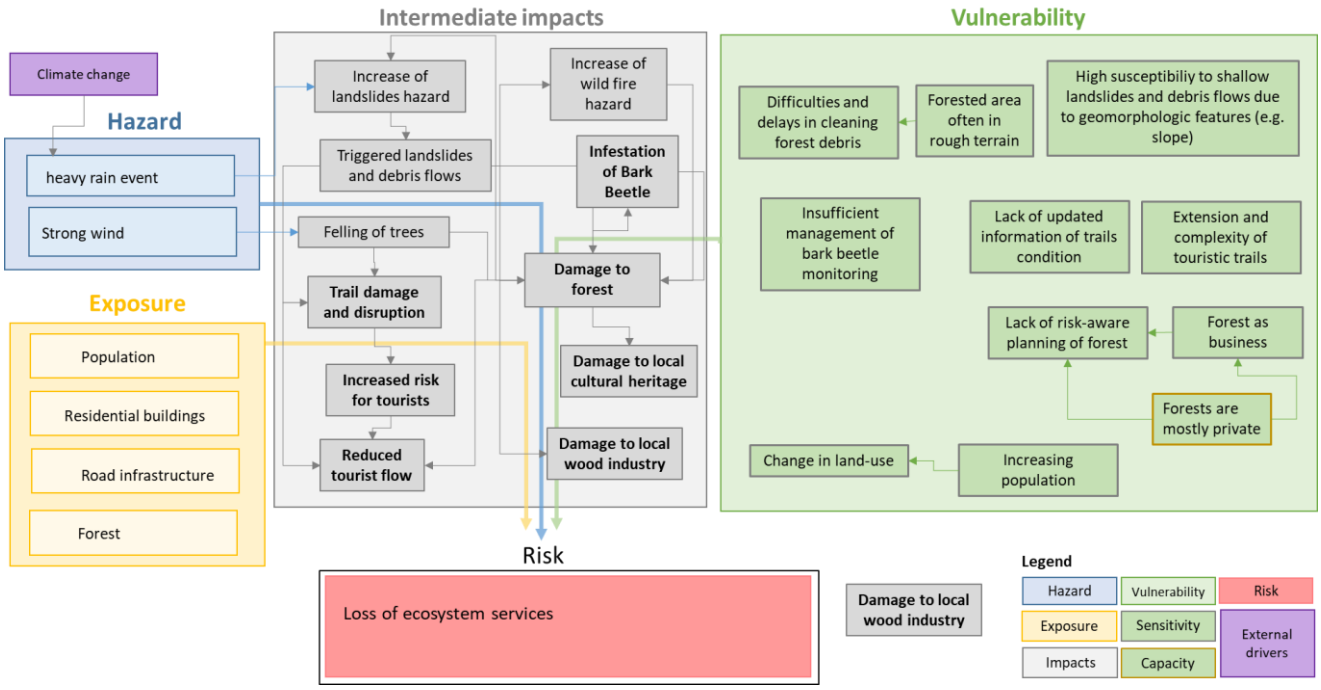

Figure 3 — Impact chains, target risk: "Loss of ecosystem services"

Further information on these impact chains can be found in the project deliverable D4.2.

2.2.1 SCREENING FOR MAIN IMPACTING MECHANISMS

An evaluation of the main factors for each risk component allows to highlight relevant elements that are expected to play a role in the impacting mechanism, or to act as powerful influencing factors. Exposure and vulnerability elements are analysed and can be linked to the other components.

This preliminary analysis provides information on the main impacting mechanisms, which allows to highlight main exposure and vulnerability components and understand at which extent the modelling of exposure and vulnerability can be carried out analytically. In particular sensitivity components can be associated to the exposure description, while other aspects of vulnerability including, e.g., lack of given institutional capabilities, cannot be accounted for quantitatively and need other approaches.
The following impact pathways have been preliminarily selected:

- Strong wind -> felling of trees -> damage to **forests**
- Heavy rain -> alpine river floods -> **road** disruption
- Heavy rain -> landslides -> **road** disruption
- Heavy rain -> alpine river floods -> damage to **buildings**
- Heavy rain -> pluvial (flash) floods -> injuries to **people**

In bold the exposed assets are highlighted and will be addressed in further detail. We can note that several hazards are considered.
We can also note that other impact pathways can be highlighted in the impact chains, referring to further exposure components (e.g., power lines) and related vulnerability factors. In this document we will consider only the components above, but further exposure components can be considered and added in the future without compromising the exemplification of the approach. Along the same line, starting from other impact chains other impacting mechanisms can be considered.

2.2.2 Highlighting main exposed assets and systems

The main factors of the exposure component that have been highlighted and selected from the impact chains include so far:

- **Population**. People can be affected directly by physical impact with the hazard factors, or indirectly due to disruption in lifelines and critical services (e.g., SAR teams, firefighters). Areas with higher population density can potentially be more exposed to natural hazards.
- **Residential buildings**. Host the population and can be affected by several phenomena either directly by physical impact, or indirectly by disruption of the utilities.
- **Road infrastructure**. Roads (and related structures such as bridges and tunnels) can be directly affected and damaged by hazards (e.g., floods or landslides) or indirectly by interruption due to, e.g., windthrows and rock falls. Roads represent both a physical asset and an infrastructure that is functional to several services (e.g., public transportation).
- **Forested area**. Forests are a very important asset in mountainous regions. They represent a valuable ecosystem service, either by their protective function, their intrinsic commercial value and their critical role as intangible socio-cultural role. Forests can be damaged and incur a loss, and can contribute directly and directly to other impacts.

These are the core of the exposure model and will be used to exemplify the approach.

2.2.3 Vulnerability-related Exposure features

Each of the exposed assets selected above can be described by a set of attributes that should provide the best information upon which to base a consistent risk assessment. This primarily entails providing information on the number or spatial extent and geographic location of the exposed assets. Besides, any further information related to the assets and relevant for their vulnerability

should be included, where possible. For instance, buildings could be described by their location (or by the shape of their footprint), but other information such as occupancy type, construction material, number of stories and other structural and non-structural features could be useful in the risk assessment. In the same way, providing demographic information on the population in a given region would integrate basic exposure with vulnerability information (e.g., share of elderly people). The list above can therefore be integrated by further information:

- **Population** (number of people in a given area, number of elderly (> 60 year), number of children (< 5 year).
- **Residential buildings** (geographic location of buildings, number of stories, main construction material / type).
- **Road infrastructure** (geographic location of roads, type -primary/secondary/tertiary, location of bridges, location of tunnels)
- **Forested area**. (geographic distribution of forested area, share of protective forest, type of dominant tree species, canopy height)

Further attributes can naturally be added, if available, although priority should be given to attributes directly related to vulnerability. A richer set of attributes might, though, allow for a later extension of the set of hazards of interest, or for the use of more sophisticated vulnerability models.

2.2.4 Define spatial resolution and aggregation

Theoretically all the exposed assets that have a countable nature should be listed thoroughly, with a so-called census approach. This can be attained when focusing on very large scale (i.e., small-area) applications, e.g. on the scale of a single city block or a small village. In larger area applications such as the case of transboundary risk assessment for intense storms, such approach is practically unfeasible, or even inappropriate for risk assessment applications. For instance, in the case of buildings or residential population providing the geographic coordinates of individual structure or people (which is also highly dynamic) is not realistic, when large-area applications are sought. In the case of population, additional concerns related to privacy protection would also apply. Furthermore, an exposure model including information on hundreds of thousands or even millions of individual assets could prove extremely challenging from the computational perspective. Last (but not least) consideration against a census-like approach is the fact that most vulnerability models and information are calibrated statistically, and as such they tend to have very low reliability when applied on very small sets of exposed assets.
Once established the need for spatially aggregating exposure information, a suitable aggregation support and an optimal resolution should be decided. The aggregation boundary can be diverse, including for instance regular or irregular grids (or other planar tessellations), or administrative boundaries or a combination of these. The choice of an optimal resolution can be driven by several considerations, including for instance: the types of hazards to be considered, the impacting mechanisms, the complexity of risk assessment approaches, the technical/computational constraints, etc.
We can note, for instance, that in the case of VAIA and similar events at least two primary hazards are present and possibly compounded: heavy rains and strong wind, and their contributions are often entangled, also including cascading impacts such as fluvial and pluvial floods and landslides. These can be considered as hazard components themselves since they are the most direct cause of damage with respect to the primary driver. The type of hazards in the considered impacting mechanism should be considered in terms of expected spatial footprint and gradient. These two

elements are in fact closely related to risk. A rather smooth spatial distribution of hazard (e.g., the average precipitation), for example, would not require very high spatial resolution. A hazard with higher expected gradient (e.g., as a pluvial flood) would instead require higher spatial resolution to account for macroscopic differences at small-area scale. For the sake of efficiency, rather than having different exposure models (one for each hazard) concurrently defined on the same area, a single multi-hazard model could be devised with an optimized resolution. Such optimal resolution would provide a trade-off between the resulting complexity of the model and spatial representation of hazard features. The optimal resolution would in turn influence the choice of aggregation boundaries. Higher spatial resolutions for instance are often not compatible with administrative boundaries and would call for regular or irregular grids and tessellations. Also, the shape of the cells of the grid/tessellation should be selected according to the same criteria.

In the case of TRANSALP, considering the hazards that are relevant for the selected mechanism we have:

Hazards	**Constrained**	**Urban / Rural**	**Gradient distance**	**Notes**
Heavy rain	no	-	~ 1km	Usual is a proxy for other hazards / impacts
Strong wind	No / partly	Mostly rural	~ 100/500m	
Landslides	partly		~ 10/100m	
Mountain river floods	yes	Mostly rural	~ 10/100m	
Pluvial (flash floods)	partly	Mostly urban	~ 10/100m	

Table 1 — Features of selected hazards relevant for exposure modelling. The attribute "constrained" refers to whether the hazard is bound to specific areas or linked to given landscape features. Attribute "Urban / Rural" refers to the environment most likely impacted by the hazards, and the "Gradient distance" attribute describes the typical distance over which the hazard can vary abruptly enough to generate unacceptable uncertainties in case of spatial aggregation.

We can note that most considered hazards can vary quite abruptly on small distances, down to few tens of meters in the case of floods and landslides, also due to the distinctive and complex morphologic features of mountain environment.
As a preliminary estimate it was deemed that a spatial resolution of around **250m** would provide an acceptable trade-off between complexity of the model and expected spatial uncertainty in the case of a fixed resolution grid.
In the case of a variable-resolution grid, the spatial resolution could vary, e.g., based on the spatial distribution of exposed assets and on other geographical features constraining the hazard distribution, but this has not been addressed in this document.

In the following section an implementation of the of the above-described methodology is provided and discussed.

3 Implementation

3.1 AGGREGATION BOUNDARY

To exemplify the exposure modelling methodology, a fixed-resolution planar tessellation based on hexagonal cells with a radius of around 250m (edge/radius $r = \frac{h}{\cos \pi/6} \approx 145\, m$, being h the centroid-to-edge orthogonal distance) has been chosen. An hexagonal tessellation is topologically more suitable than a common square grid (Birch, Oom, & Beecham, 2007). Hexagons reduce the sampling bias due to their low perimeter-to-area ratio, and neighbouring locations are all at the same distance from a cell. Furthermore, a tessellation of regular hexagons is also a Voronoi diagram, hence all points within an hexagon are closest to its centroid than any other Delaunay/centroid point in the region, implying a better spatial representativeness of each cells.
A portion of the tessellation, which we will refer to as $\mathcal{H}_{250}$ throughout the document, is shown in Figure 4.

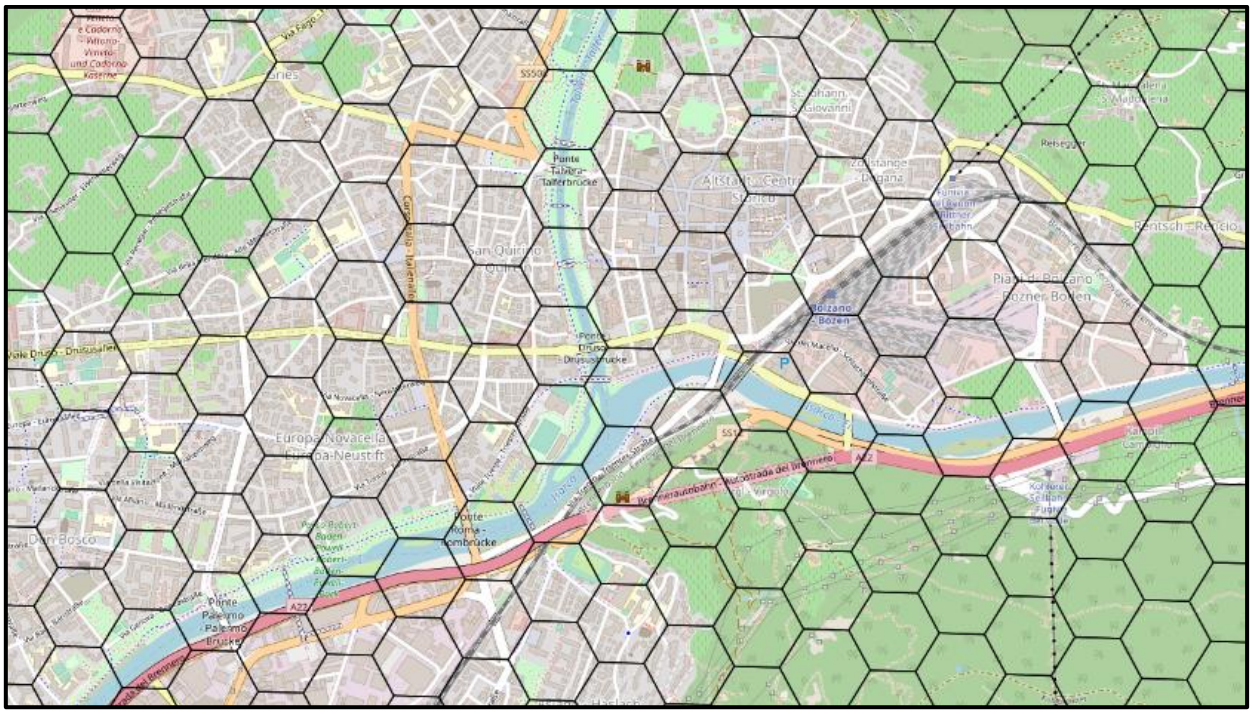

Figure 4 — An overview of the test $\mathcal{H}_{250}$ tessellation over Bozen/Bolzano (OpenStreetMap tiles in the background).

The resulting tessellation covers the geographic span of South-Tyrol, the main study area, with 119'911 cells, and the overall study area with 163'313 cells. The resulting model has relatively high spatial resolution, yet the complexity of the model is not exceedingly high and can still support affordable processing routines. The tessellation can be further extended to include other areas or cover other regions, in a dynamic fashion.

3.2 AREA-BASED EXPOSURE

Each of the cells in the tessellation provides a support for aggregating the different features and assets describing the vulnerability model. Based on the considerations in section 2.2.3, the information described in Table 2 below has been included in the aggregation process.

Environmental features
1. Land cover / land use (in % of cell area), according to a simplified schema, including:

a. Sealed surfaces **b.** Protective forest
Exposed Assets
Places/Sinks of presence of people: 1. No. of Buildings (individual structures, possibly separating residential, industrial and commercial buildings) 2. No. of resident people 3. No. of Hospitals 4. Total capacity of hospitals 5. No. of Care and elderly care centres 6. Total capacity of elderly care centres 7. No. of Educational facilities (schools) o Schools 8. Total capacity of schools 9. No. of Tourists accommodations o Hotels & Inns o Farm stays 10. Total capacity of tourists accommodations
Transport Infrastructure: 1. Main Roads (total m of roads - motorway/trunk/primary) 2. Drivable Roads (total m of other drivable roads)

Table 2 — Environmental features and asset information aggregated at cell level.

As a preliminary version of the exposure model, this information includes several relevant exposed assets related to the socio-economic system: building structures, people (including children and elderly), tourists, hospital and day-care system, as well as road transportation. In the case of forested areas, this parameter conveys both exposure and environmental information, and is associated to land-use/land-cover information. These parameters provide an efficient and integrated support for risk assessment in case of storms and other complex events including multiple natural hazards. The model can also be easily extended to encompass further information to improve the thematic resolution of the exposure model and to accommodate for further hazards of interests.

component	Count	Mean	std	min	max
No. of residents	13089	40.0	108.9	1	1715
Capacity tourism accommodations	4534	41.9	65.7	1	811
Capacity schools	494	173.3	277.2	5	2497
Capacity Elderly care centres	75	59.2	31.5	21	170
Beds day-care hospitals	7	24.3	24.9	4	78
No. Hospitals	7	1.0	0	1	1
No. Elderly care centres	75	1.0	0.1	1	2
No. of Tourists accommodations	4911	2.0	2.4	1	31
No. of schools	499	1.7	1.0	1	-

Table 3 — Basic cell summary and cell-based statistics of the countable exposed assets considering the South-Tyrol area.

In Table 3 a basic cell summary and cell-based statistics of the countable features of the exposure model considering South-Tyrol (only where the corresponding cell attribute is greater than zero) is provided. We can for instance note that over 13’000 cells have a non-zero number of residents, with a maximum number of residents per cell equal to 1’715.

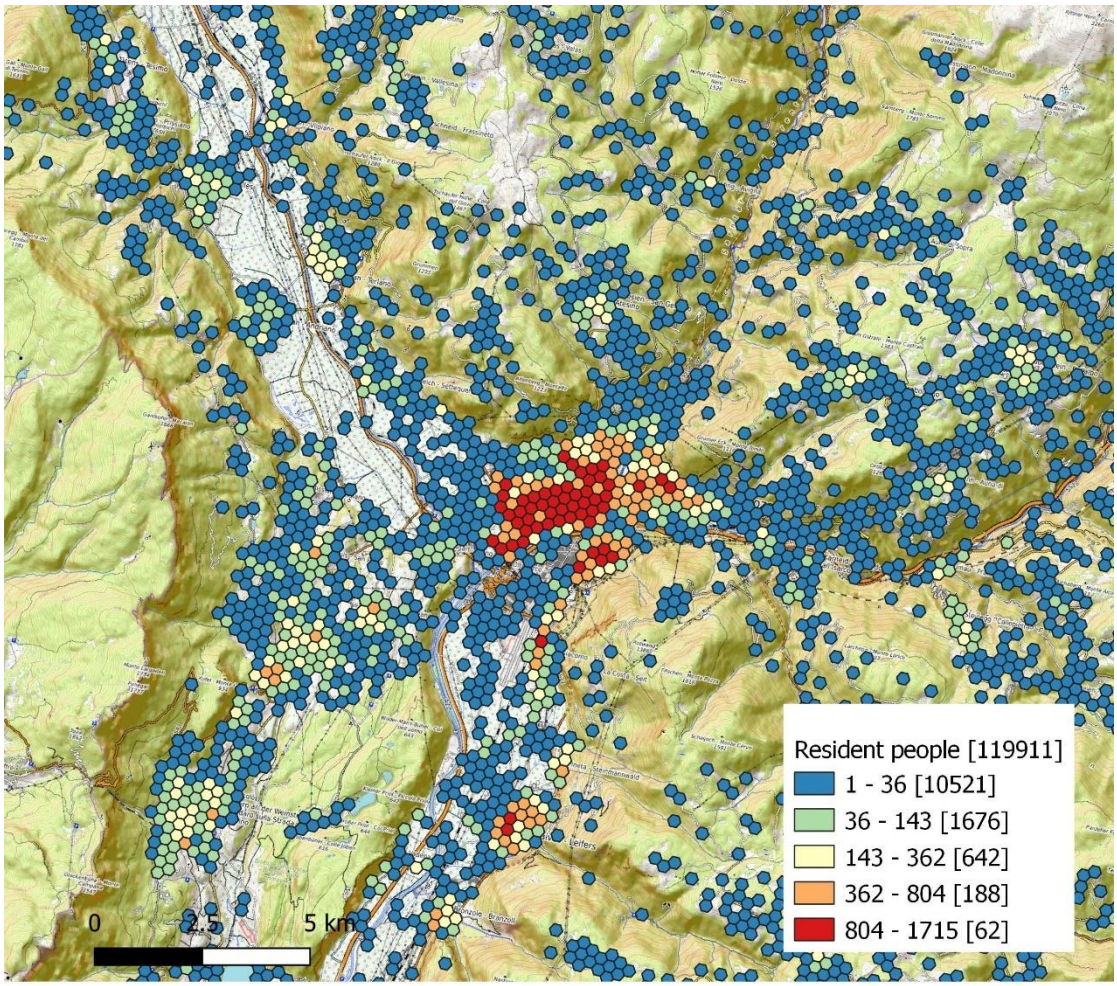

Figure 5 — Integrated exposure model: distribution of resident population (aggregated total number of people, only non-zero cells visualized). In parenthesis the number of cells related to the different value ranges.

Two visualizations of the resulting exposure model are provided in Figure 5 and Figure 6, respectively showing the distribution of resident population and the distribution of aggregated school capacity in the area of Bolzano, in South Tyrol. Only non-zero cells are displayed. We can note that, being the information on the different exposed assets already aggregated at the cell level, it is straightforward to visualize (or use in further processing steps) the related features.
This harmonization allows for an easier employment of the resulting model in risk-oriented applications.
We can also note that the exposure information provided in the model is strictly related to the expected vulnerability of the assets with respect to the considered natural hazards, even in the case where vulnerability or sensitivity factors were not explicitly considered. For instance, the number and total capacity of schools provides information on the potential presence of children in the area, whereas the number and total capacity of elderly care centres is a proxy for the presence of elderly people.

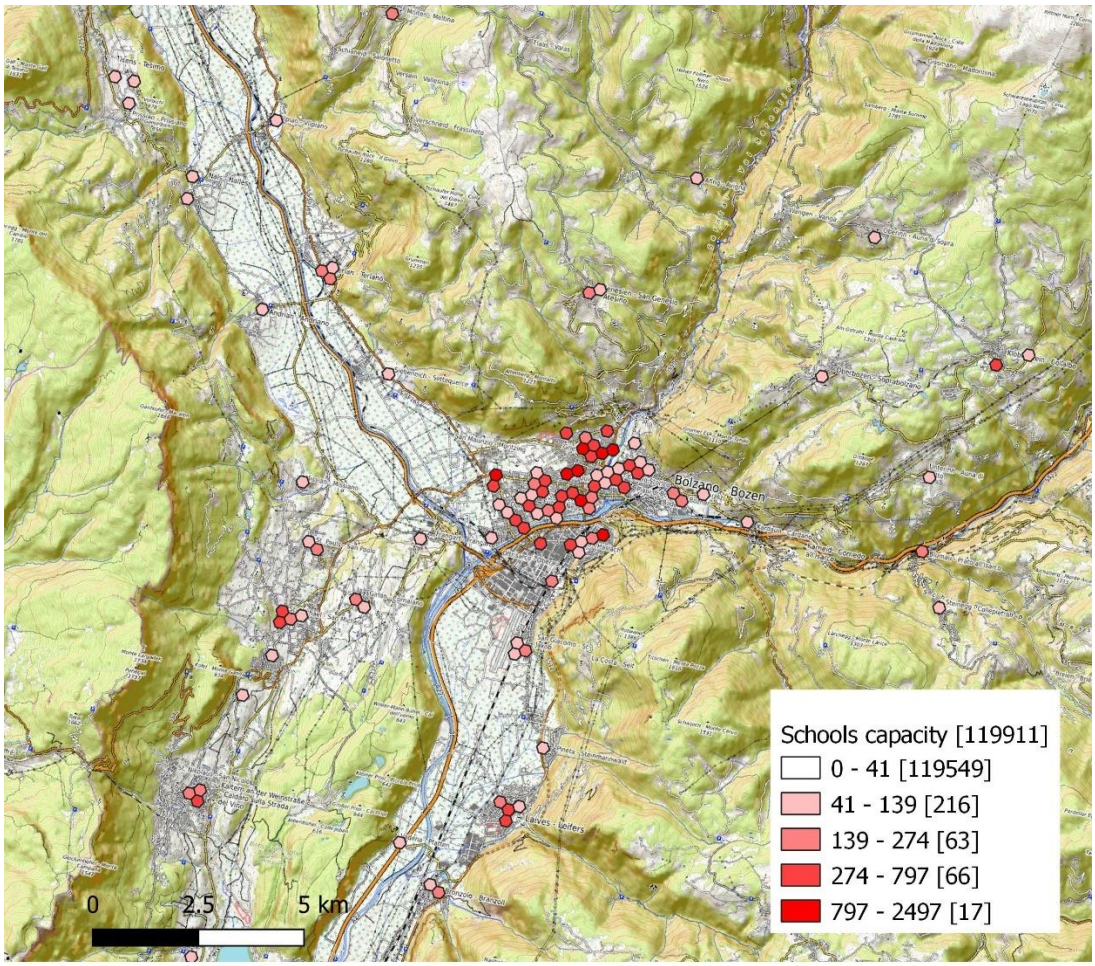

Figure 6 — Integrated exposure model: distributio of school capacity (aggregated number of pupils, only non-zero cells visualized). In parethesis the number of cells related to the different value ranges.

A further visualization of the exposed assets is provided in the Appendix 1.

3.3 Roads infrastructure

The roads network is an important component of risk, since it provides the main transport infrastructure in most inhabited areas, granting both the movement of people (e.g., from and to the working place) as well as the movement of emergency and civil protection authorities. As emerges from the impact chain analysis, road infrastructure is exposed to several hazards through different impacting mechanisms, e.g., can be directly damaged or otherwise impaired by temporary physical obstructions (e.g., floods). As such it is a basic component of exposure in many risk-oriented models. Furthermore, unless other exposure components, in the case of roads not only the spatial location and features of the assets are important, but also their topological features, including for instance information on their connectivity. In fact, a relatively light or temporary damage which is completely obstructing a primary road is much more impactful than a more serious structural damage not impairing the circulation. This is particularly relevant in the case of mountainous regions, where the road network is usually topologically vulnerable due to the lack of redundancy induced by the geomorphologic constraints of the landscape.
In order to consider this aspect, the road network should not only be provided in aggregated form in the cell-based description, but also as a separate vector layer. The practical use of such layer in

risk-oriented application can anyway result challenging, due to the complexity of the road network even in relatively less dense areas, in mountain regions. For instance, the road network derived in South Tyrol from free and open source datasets (OSM) has 7'900 km of primary, secondary and tertiary roads (considering only drivable roads) with 21'349 intersections and 48'000 road segments. To reduce the complexity of the problem, without losing the related topological information, and also to efficiently include the information on roads infrastructure into the exposure model, an equivalent representation based on the integration of spatial tessellations and graphs has been explored, as shown in Figure 7. In this case the area covered by the hexagonal mesh can be functionally represented as a graph whose nodes represent the exposed assets in the related polygonal cells, and whose edges represent the equivalent flow capacity of the roads crossing the borders with adjacent cells.

This type of approach would provide a trade-off between model computational complexity, uncertainty, and scalability and hence an actionable solution for the perspective use in operational applications. The integration of topological models for the transport infrastructure and the combination with static and possibly dynamic exposure modelling has a two-fold benefit: it increases the realism of the output model, and it allows for a better analysis of the systemic vulnerability. The calibration of the model has been conducted in South Tyrol using available data from authoritative sources, such as for instance housing and population censuses and local administrative databases.

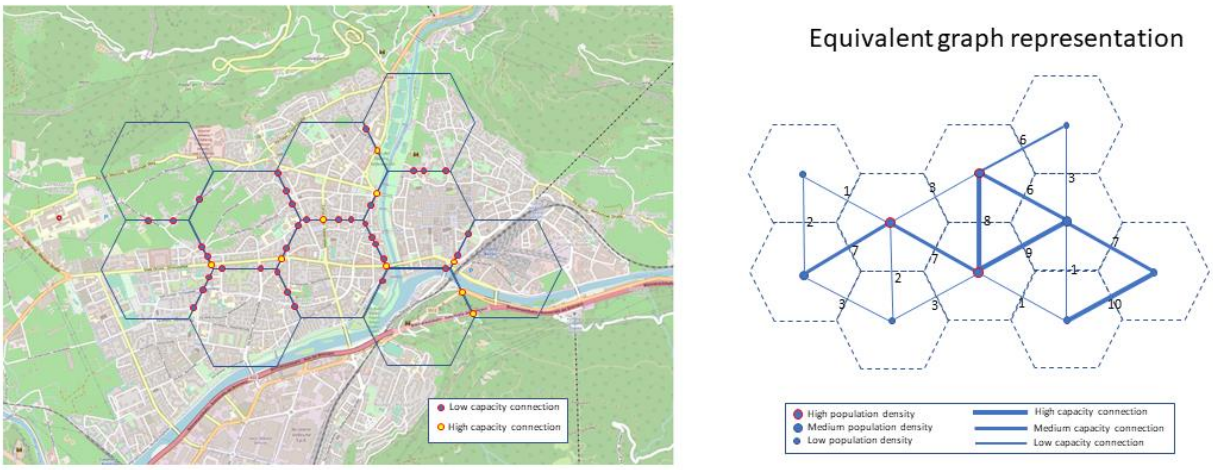

Figure 7 — Example of mesh-based modelling (left) and equivalent graph representation (Right). The numbers represent the nominal capacity of the arcs, obtained by summing up the capacity of the roads crossing the cells borders. The connections are depicted on the left; low and high-capacity connections contribute respectively with 1 and 5 to equivalent arc capacity.

The simplification of the original roads network against the $\mathcal{H}_{250}$ tessellation is therefore obtained through the implementation of a graph G_{250} whose nodes n_i coincide with the hexagons' centroids. The original road information has been extracted from the free and open source OpenStreetMap database. For the sake of simplicity we selected only the drivable roads, which is obtained by the following filtering on roads tags in the download query (the API Overpass was used to this purpose):

```
["highway"!~"abandoned|bridleway|bus_guideway|construction|corridor|cycleway|
            elevator|escalator|footway|path|pedestrian|planned|platform|proposed |
            raceway|service|steps|track"]
["motor_vehicle"!~"no"]
["motorcar"!~"no"]
["service"!~"alley|driveway|emergency_access|parking|parking_aisle|private"]
```

Listing 1 — Overpass QL excerpt used to filter the "drivable" roads graph from the OSM database – taken from the source code of the OSMnx Python library (Boeing, 2017).

The algorithm used to obtain the simplified graph is described in Listing 2. Put simply, the algorithm collects all the roads intersecting the border between two contiguous locations h_i and h_j, assigns a weight proportional to their type, then assigns it to a fictitious road connecting the two locations' centroids.

```
01. ALGORITHM graph-tessellation IS:
02.    LET H be the hexagonal tessellation
03.    LET R be the input OSM roads graph
04.    LET G be the tessellated roads graph
05.
06.    FOR each location h(0) in H:
07.       LET c(0) be the centroid of h(0)
08.       IF c(0) is not in G:
09.          ADD node c(0) to G
10.          FOR each location h(i) neighbour of h(0):
11.             LET c(i) be the centroid of h(i)
12.             LET e(0,i) be the edge connecting c(0) and c(i)
13.             IF e(0,i) is not in G:
14.                LET b(0,i) be the border line between h(0) and h(i)
15.                LET r[] be edges of R intersecting with b(0,i)
16.                LET N(i) be the cardinality of r[]
17.                IF N(i) is greater than 0:
18.                   INIT W(i) to 0 as the total weight of b(0,i)
19.                   FOR each edge r(n) in r[]:
20.                      COMPUTE weight of r(n) RETURNING w(n)
21.                      ADD w(n) to W(i)
22.                   ENDFOR
23.                   SET attribute "count" to N(i) on edge b(0,i)
24.                   SET attribute "weight" to W(i) on edge b(0,i)
25.                   ADD edge b(0,i) to G
26.                   ADD node c(i) to G
27.                ENDIF
28.             ENDIF
29.          ENDFOR
30.       ENDIF
31.    ENDFOR
```

Listing 2 — Pseudo-code of the algorithm used to simplify/tessellate the OSM roads dataset onto the $\mathcal{H}_{250}$ hexagonal tessellation.

As regards to the calculation of the total weight of each edge in the original graph R — see line 20 of Listing 2 — the algorithm assigns a weight of 1 to each intersecting road, plus an additional weight based the OSM *highway* tag[1] as per the following table.

[1] See the "Key:highway" page in the OSM Wiki for a full up-to-date description of the tag usage and values: https://wiki.openstreetmap.org/wiki/Key:highway

"highway" tag value	weight
motorway	10
trunk	10
primary	8
secondary	5
tertiary	3

Table 4 — Additional weights assigned to an OSM road hitting the border of two cells of the $\mathcal{H}_{250}$ tessellation, based on the value(s) of its `highway` tag.

A cutout of the resulting simplified graph G_{250} over the municipality of Bozen/Bolzano is shown in Figure 8.

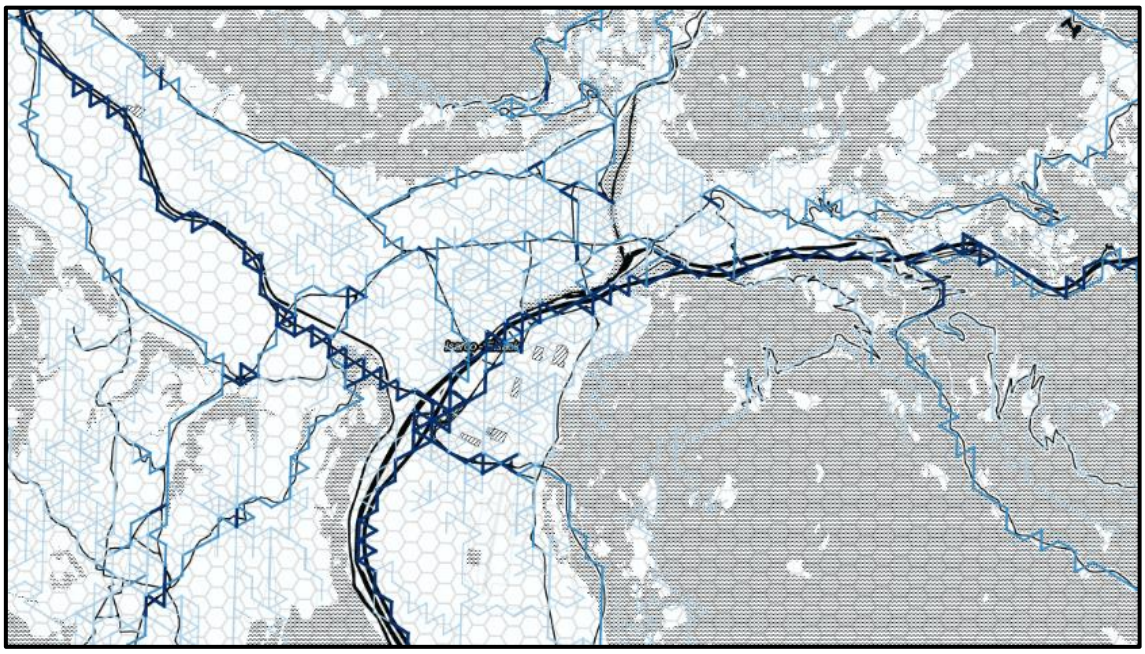

Figure 8 — Visualization of the drivable OpenStreetMap (OSM) roads graph over the area of Bozen/Bolzano after being projected onto the hexagonal tessellation. The original OSM roads dataset are also visible in the map. The gradient of blues and thickness of the edges in the graph encode the weight assigned to each edge in the simplified graph.

In Figure 9, the equivalent graph and the underlying aggregation boundary (i.e., the hexagonal tessellation) are shown. The resulting structure is providing a consistent modelling of both the exposed assets (aggregated over the cells of the tessellation) and the topological connectivity among the cells of the tessellation induced by the underlying road network. The hexagonal shape of the cell allows for a smoother representation of the connectivity while the weighting scheme used to aggregate the raw information on the roads provide a good indication of the total road capacity in each cell.

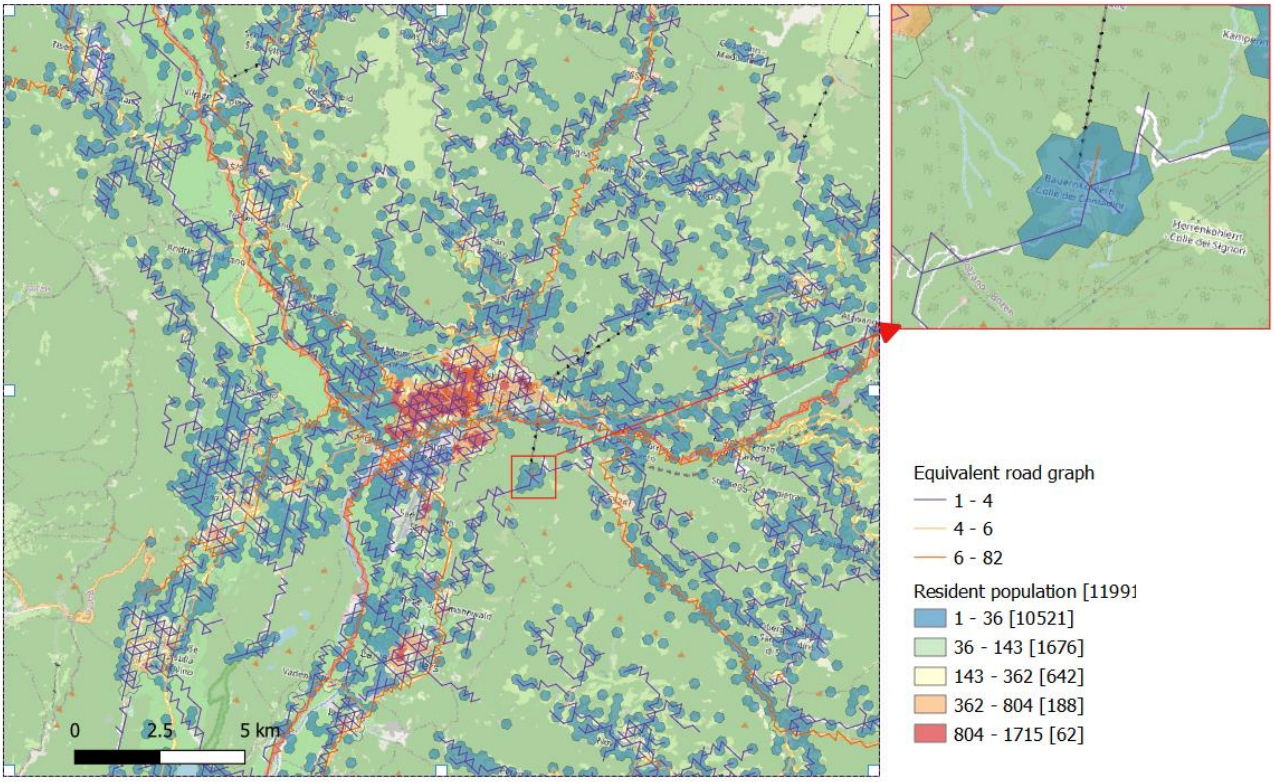

Figure 9 — Visualization of the integrated exposure model including the aggregation boundary (hexagonal tessellation) and the equivalent graph model, color-coded according to the intensity of connectivity.

The resulting equivalent graph has 11'589 intersections, 55% of the non-simplified one, therefore indicating a strong reduction in the complexity of the functional and topological representation. Since the simplified connection take into account the number and type of roads connecting neighbouring cells, this equivalent representation can still be used to model the expected movement of population across the tessellated model.

3.4 VULNERABILITY

The vulnerability of the exposed infrastructure will be modelled following a two-tier approach. The first tier relates to the description of the physical fragility of the assets (or parts thereof). Existing fragility models as proposed in literature (e.g., developed within the Syner-G and LessLoss projects) can be used according to the specific considered hazard, also considering the information available on both the structural features of the exposed assets and the extent to which the hazard intensity (floods or landslides in our case) can be modelled / retrieved. Pragmatic solutions based on simplified / proxied models could be employed, also integrated by expert-judgment, where necessary. Currently in the case of the hazards related to strong storms, there are no available fragility models, therefore this aspect of physical fragility has to be further assessed by collecting and analysing additional data.

The second tier of vulnerability refers to the analysis of the functional performance of the infrastructure and how it can be impacted by physical damage, hence possibly resulting in a systemic damage / loss. The functional modelling of the transport network will be based on its topological description (i.e., the adjacency / connectivity relations among the individual elements) in terms of graph theory and complex networks. Equivalent functional models can, for instance, be explored, at different spatial resolution. The analysis of the network flow (by means of numerical simulations)

with different physical damage patterns will highlight the potential critical elements (that is, those elements whose damage or interruption would lead to a critical state of the network´s functionalities). The assessment of network´s functionality can be based on different criteria, including for instance the loss of connectivity between different settlements or between areas within a given settlement. This is especially relevant in mountain areas where, due to the strong topographic and morphologic constraints (presence of narrow valleys and mountains) interruptions of roads due to landslides and rock-falls can lead to entire communities being cut-off. As an outlook, a dynamic estimation of reachability for given critical locations or infrastructure (e.g., hospitals, fire stations, emergency response coordination centres) will contribute to better understand the systemic impact of the considered natural hazards.

In Figure 10 for instance, the topological vulnerability of the road network is shown in terms of the "betweenness centrality" of the equivalent (non-simplified) graph. This indicator describes the criticality of each road segment as a functional connectivity element. Roads segments with higher betweenness centrality, if interrupted, will likely result in a significant disfunction of network connectivity.

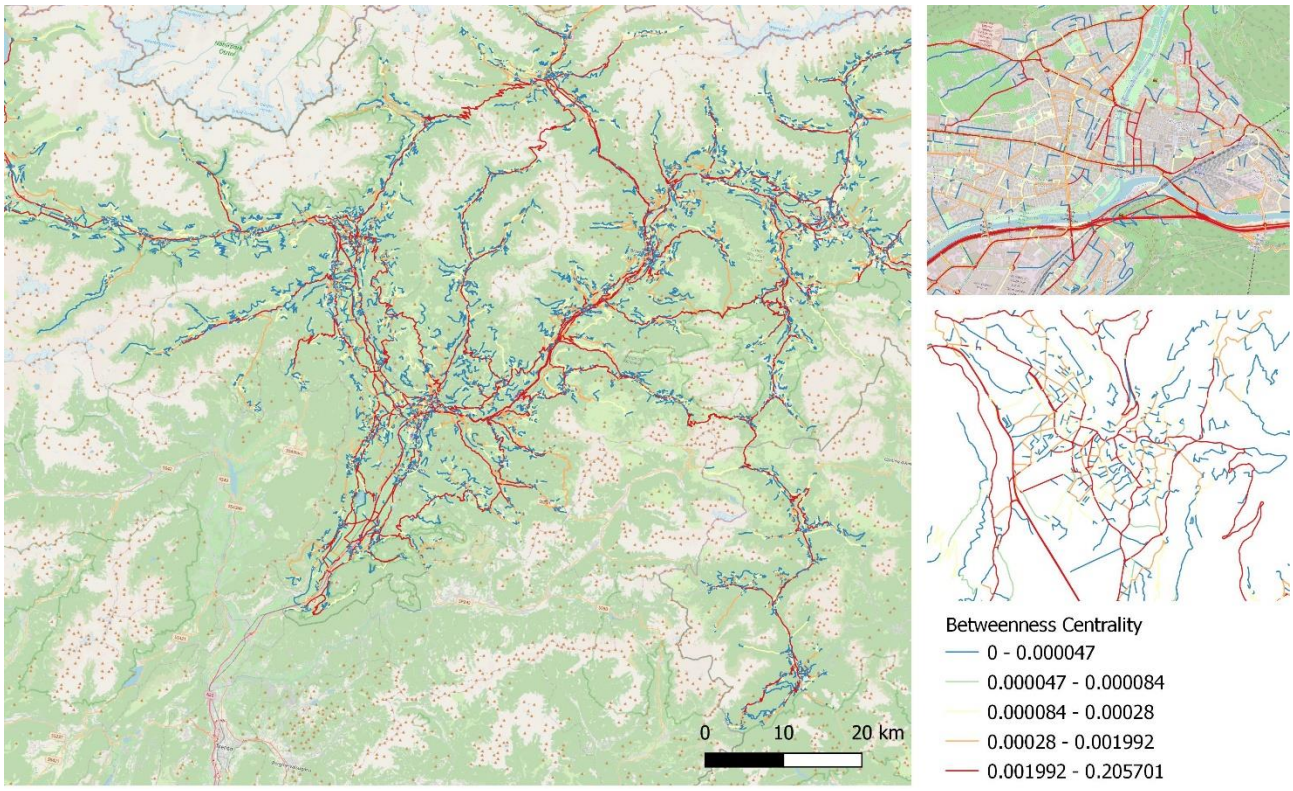

Figure 10 — Betweenness Centrality vulnerability indicator computed for the South Tyrol roads network. The two insets on the right side depict respectively Bolzano (upper) and Merano (lower side).

We can note that the specific morphology typical of mountainous regions results in a high amount of critical road segments. We also note that by construction this indicator will also describe what roads will be subjected to the heaviest traffic, which is another potential vulnerability proxy (e.g., with respect to air pollution). The two insets in the figure also show the distribution of critical road segments within two main urban centres in the region.
Another topological indicator for vulnerability can be provided in terms of the "reachability" of given critical asset along the road network. The reachability is described in terms of the distance, along

the shortest path on the road network, of each intersection from the considered critical asset. For instance, in Figure 11 the reachability of hospitals in South Tyrol is shown.

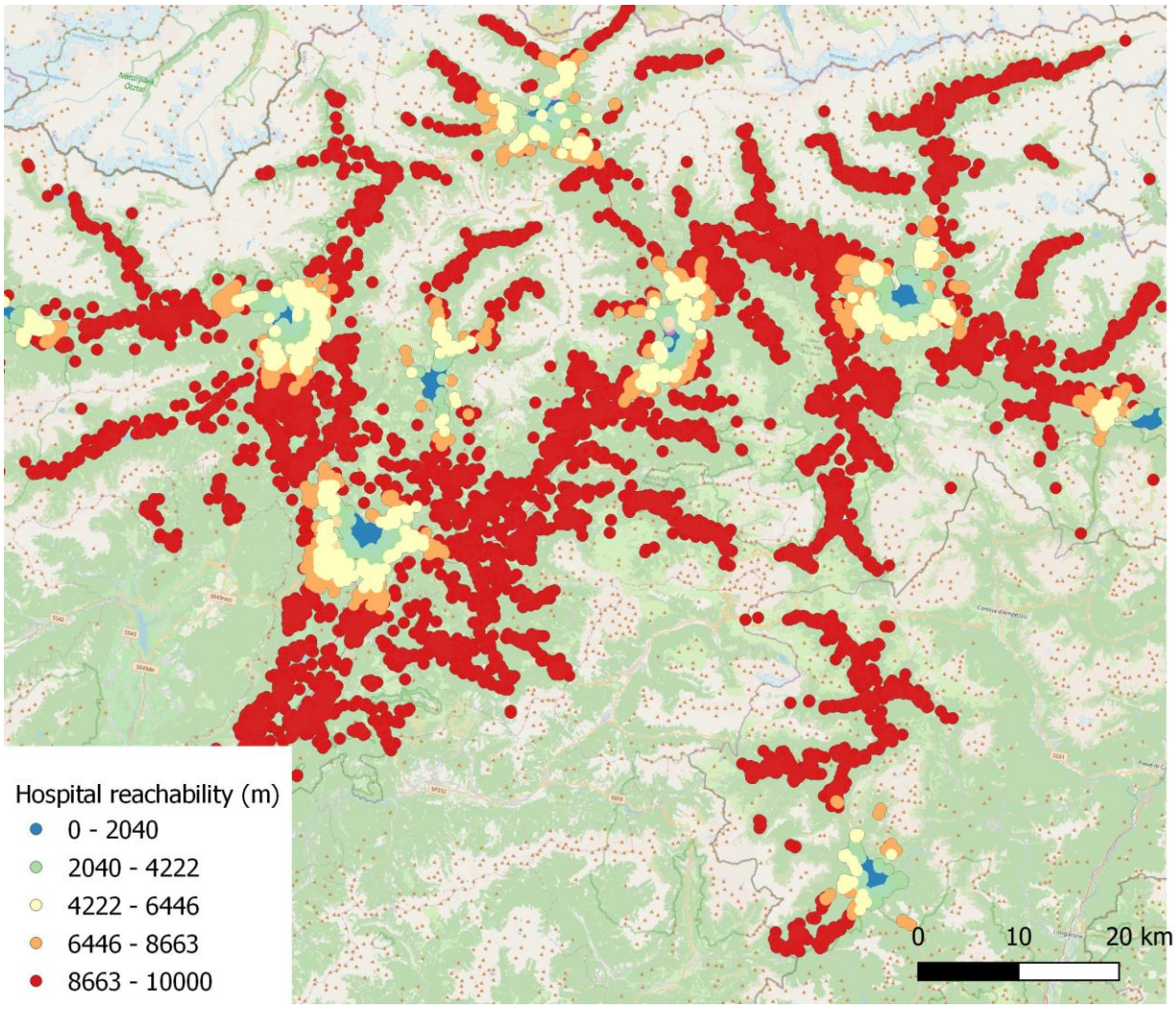

Figure 11 — Reachability of hospital structures in South Tyrol over the drivable roads network. The higher the value, the further is the nearest hospital.

It is possible to note that a clear majority of locations on the road network lie at least 8.6 km away from the nearest hospital, due to a combination of few hospitals and a poorly connected road network (for the topological constraints described above). We note that the reachability is computed considering the shortest path on the road network, therefore many locations, although relatively close to hospitals at bird´s fly, are in fact poorly connected. The reachability parameter can be computed for other critical or relevant locations including pharmacies, food markets, schools, etc.

3.5 Dataset

The dataset implementing the exposure information described in this document is further documented in the companion deliverable D4.4 and available for download in the project´s online repository.

4 CONCLUSIONS

This document describes an integrated exposure and vulnerability model to support the assessment of risk due to intense storm events. The proposed model is based on an innovative combination of planar hexagonal tessellation, used as an aggregation boundary to describe different types of exposed assets, and a connected graph structure describing the topological connectivity among the cells of the tessellation according to the actual geometry of the drivable road network in the study area. This combination allows for integrated assessment of exposure and vulnerability, both in terms of sensitivity factors implied by the recorded features of the exposed assets and in terms of the topological features of the road network upon which people and good are constrained to move from one cell to another.

As outlook, the resulting model can be further extended by exploiting its explicit connectivity information to model the exposure also dynamically, e.g., by considering the ordinary (e.g., commuting) and extraordinary (e.g., evacuation) displacement of population over time in the considered area.

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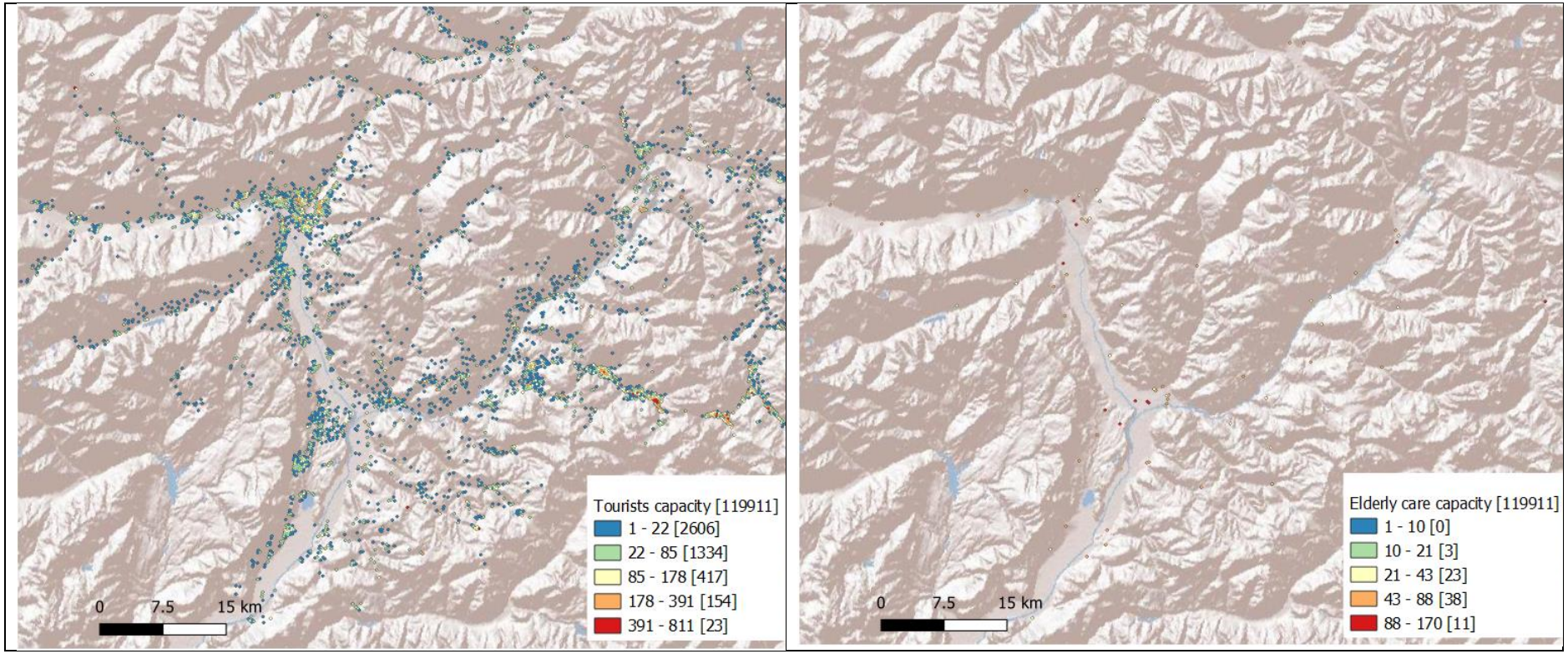
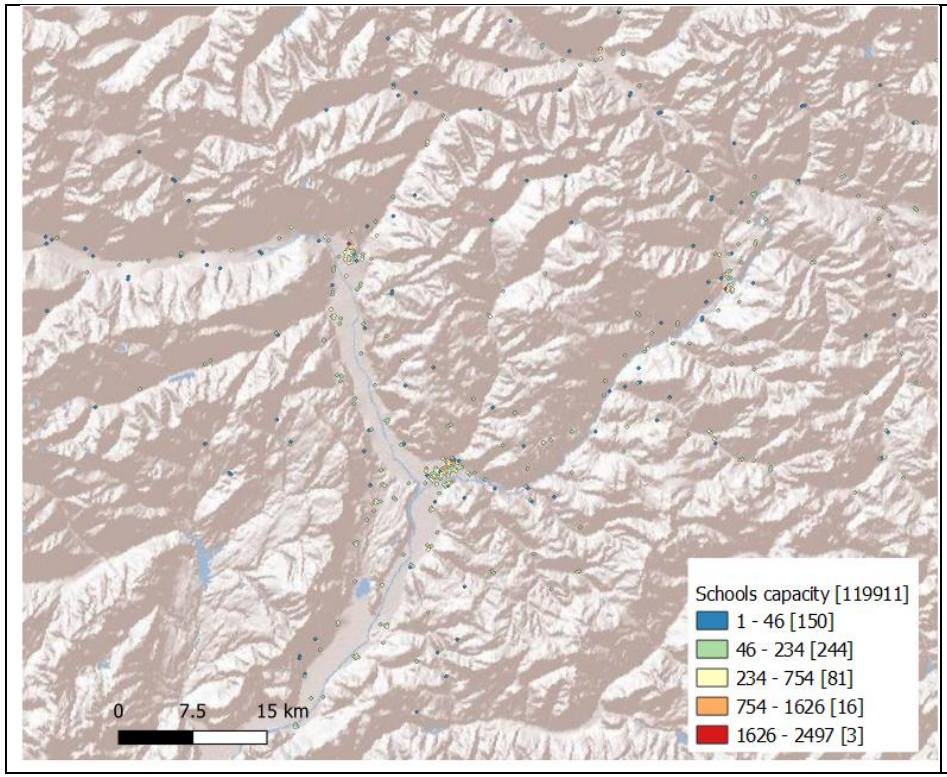
6 APPENDIX 1


Tourists capacity [119911]
1 - 22 [2606]
22 - 85 [1334]
85 - 178 [417]
178 - 391 [154]
391 - 811 [23]
0 7.5 15 km
Elderly care capacity [119911]
1 - 10 [0]
10 - 21 [3]
21 - 43 [23]
43 - 88 [38]
88 - 170 [11]
0 7.5 15 km


Schools capacity [119911]
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754 - 1626 [16]
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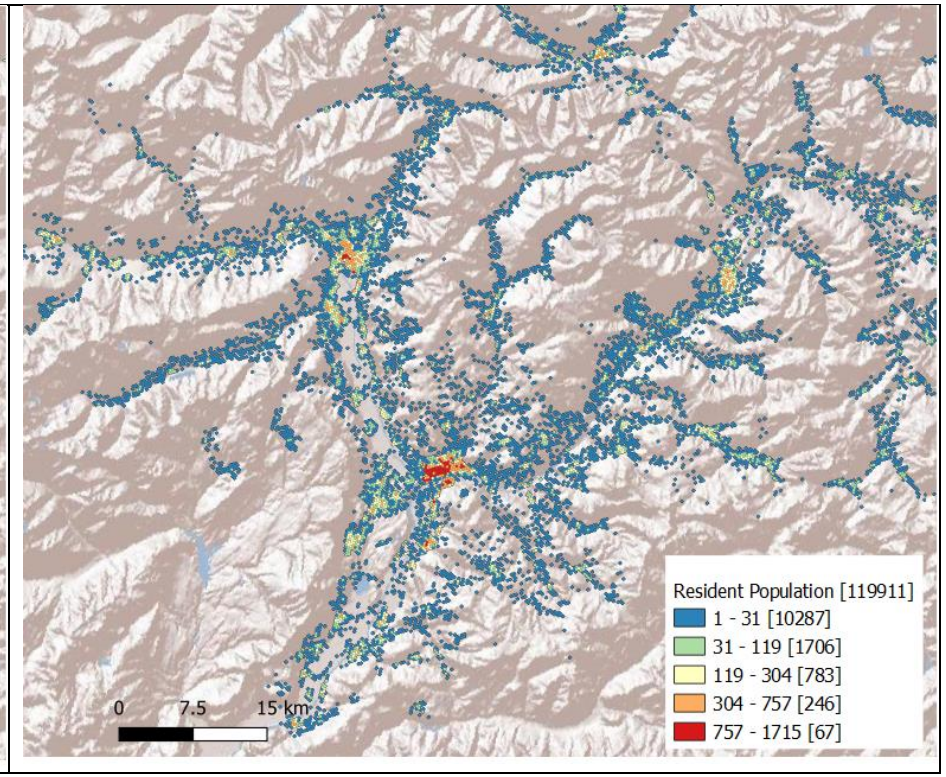
0
7.5
15 km


Resident Population [119911]
1 - 31 [10287]
31 - 119 [1706]
119 - 304 [783]
304 - 757 [246]
757 - 1715 [67]
0
7.5
15 km