

Article

# Urban Population Flood Impact Applied to a Warsaw Scenario

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**Abstract:** The provision of detailed information on the impact of potential fluvial floods on urban population health, quantifying the impact magnitude and supplying the location of areas of the highest risk to human health, is an important step towards (a) improvement of sustainable measures to minimise the impact of floods, e.g., by including flood risk as a design parameter for urban planning, and (b) increase public awareness of flood risks. The three new measures of the impact of floods on the urban population have been proposed, considering both deterministic and stochastic aspects. The impact was determined in relation to the building's function, the number of residents, the probability of flood occurrence and the likely floodwater inundation level. The building capacity concept was introduced to model population data at the building level. Its proposed estimation method, an offshoot of the volumetric method, has proved to be successful in the challenging study area, characterised by a high diversity of buildings in terms of their function, size and density. The results show that 2.35% of buildings and over 122,000 people may be affected by 500-year flooding. However, the foreseen magnitude of flood impact on human health is moderate, i.e., on average ten persons per residential building over the 80% of flood risk zones. Such results are attributed to the low inundation depth, i.e., below 1 m.

**Keywords:** urban population estimation; building capacity; flood impact; GIS modelling; flood mitigation



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## 1. Introduction

Flooding is one of the most disruptive natural hazards in the world [1–3]. According to the World Health Organization [4], flooding has affected more than 2.3 billion people worldwide in the last twenty years (1998–2017) and is responsible for 47% of weather-related disasters. Devastation caused by floods can lead to loss of life, damage to property, public infrastructure and nature. Between 1900 and 2014, floods have had the second highest death rate (30%) of all natural disasters [5]. Losses are particularly severe in densely populated and intensely developed urban areas. Roudier et al. [6] established that if global warming reaches +2 °C, the floods' magnitudes will increase in almost all European countries, with a significant upsurge in Northwest Europe. Furthermore, they noticed that the increase in 100-year floods would be much greater than that in 10-year floods. The possible upsurge in the severity of floods was also noticed by Rojas et al. [7]. Blöschl et al. [8] observed a distinct shift in the timing of floods in Europe over the past five decades. Moreover, Blöschl et al. [9] showed that the escalation of floods events in northwestern Europe resulted from higher fall and winter rainfall, while decreasing precipitation and increasing evaporation led to a reduction of floods in southern Europe. Eastern Europe, due to warmer spring temperatures and decreasing snow cover, felt the effects of floods less frequently. Tanoue et al. [10] found that the flood risk forecast is influenced by different scenarios of population growth and population spatial distribution. Furthermore, the availability of detailed and reliable spatial and socio-economic data plays a significant role in estimating flood risk zones and developing flood risk management and

mitigation [11]. The uncertainty of forecasts resulting from the use of different scenarios and different models of climate change were also reported by Roudier et al. [6].

Urbanisation, climate change, topography and the hydrological regime are the main factors determining the probability of inundations [10,12,13] while economic growth results in higher costs of removing the effects of flooding [14]. Due to the concentration of population, dense built-up and other infrastructure necessary for the economic and social well-being of societies and the amount of losses caused by floods, urban areas are of concern to both scientists and practitioners. World literature extensively covers the problem of buildings and populations prone to flooding at all levels, from local to global [15,16]. Knowing the exposure to flooding is one of the elements of flood risk assessment for buildings and people, and thus essential for the preparation of appropriate risk management plans [17]. However, as found by Papilloud et al. [15] the concepts of flood exposure and flood vulnerability are understood differently, which results mainly from the disciplinary backgrounds as well as research aims and questions. As shown in the literature, flood exposure is not only defined ambiguously but also analysed with various approaches and methods [15,18,19]. The most common approaches are based on geographic information system (GIS) technology and methods, in particular the spatial overlap, intersection or spatial joint of flood hazard zones and buildings.

The use of GIS methods in flood exposure assessment can be found in global [10], national [20], regional [21] and local studies [18,19,22]. Nevertheless, this type of flood exposure analysis requires geographic data on building locations, gridded population data and the geographical extent of flood risk zones [22]. Furthermore, Jongman et al. [16] noted that the results of global exposure analyses, in particular the differences in estimates and geographic distribution, are strongly dependent on the methods used. This was also confirmed by Hirabayashi et al. [23] and Tanoue et al. [10] who applied different scenarios to predict the global threat to the population caused by floods triggered by climate change. Tanoue et al. [10] found that the characteristics of the population exposed to floods are influenced by historical changes in population distribution, with changes in vulnerability to floods reaching 48.9%. The number of people affected by flooding was calculated by the spatial overlaying of the flooded area with the global gridded population. Röhrlisberger et al. [20] focused on the problem of data analysis in various risk-based strategies and noted that the analysis of exposure is highly dependent on the availability, spatial resolution and quality of data, namely data on assets (e.g., affected people, buildings and infrastructure) and on the nature of the hazards (i.e., the extent and magnitude of the flood). Bholá et al. [19], inspired by Kolen et al. [24], presented an approach based on a combination of multiple models by considering several exceedance probability scenarios to better support decision making in crisis management. Finally, they proposed a building hazard map, in which flood-affected buildings are marked with varying probabilities of exceeding the flood inundation extent depending on the building use.

Analysing the exposure of the population to urban floods, many studies focus on estimating the people counts at a micro-scale, particularly at the building level. Zhu S. et al. [25] mapped the building-scale population by calculating the correlation coefficient between the POI (point of interest) type and WorldPop population grid to establish the relationship between building function and population distribution in Lishui City, China. Darabi et al. [26] applied machine learning algorithms to predict flood hazard probabilities; they created a vulnerability map and assessed risk as a product of hazard and vulnerability. The factors influencing flood hazard the most were distance to channel, land use, and runoff generation, while population density and building density were the most important factors determining vulnerability. Hossain and Meng [18] aimed to assess the potential risk of damage caused by the exposure of buildings and populations to flooding in urban areas (Birmingham City, AL, USA). The developed GIS-based risk assessment model showed the level of flood risk, quantified and simultaneously mapped commercial buildings, residential buildings and populations at risk of flooding. The findings of Hossain and Meng [18] revealed that approximately 44% of the total population of the Birmingham floodplain area



lived in high and very high flood risk zones. Calka et al. [22] estimated the people counts in buildings based on the regression between a building's footprint area, the building's type (single-family, twin, multi-family), and the average number of people living in one household. The study found that about 30% of residents of villages located on the Bug River floodplain (eastern part of Poland) lived in high flood risk areas.

Several factors vitally influence the extent of flood damage, i.e., water depth, flow speed, geographical extent and duration [27]. However, the factor most commonly applied in studies is water depth, e.g., [15,18,25,27–29]. Flood risk also depends on the types of assets exposed, therefore many studies focused on buildings and road infrastructure, as examples of structural flood damage. Some academics evaluated buildings damaged using the appraisal value [28], while others used the building characteristics [30,31]. There is a broad consensus, however, that as a priority loss of life must be prevented by all means possible [13]. Disaster mitigation efforts increasingly focus on the exposure and vulnerability of human populations [32]. For example, the perception of flood risk among the population is being studied, constating that it is underestimated, and steps are being taken to change this [33–35]. This consequently translates into increasing the awareness of potential flood risks, the preparedness for an emergency case and the willingness to cooperate [35,36].

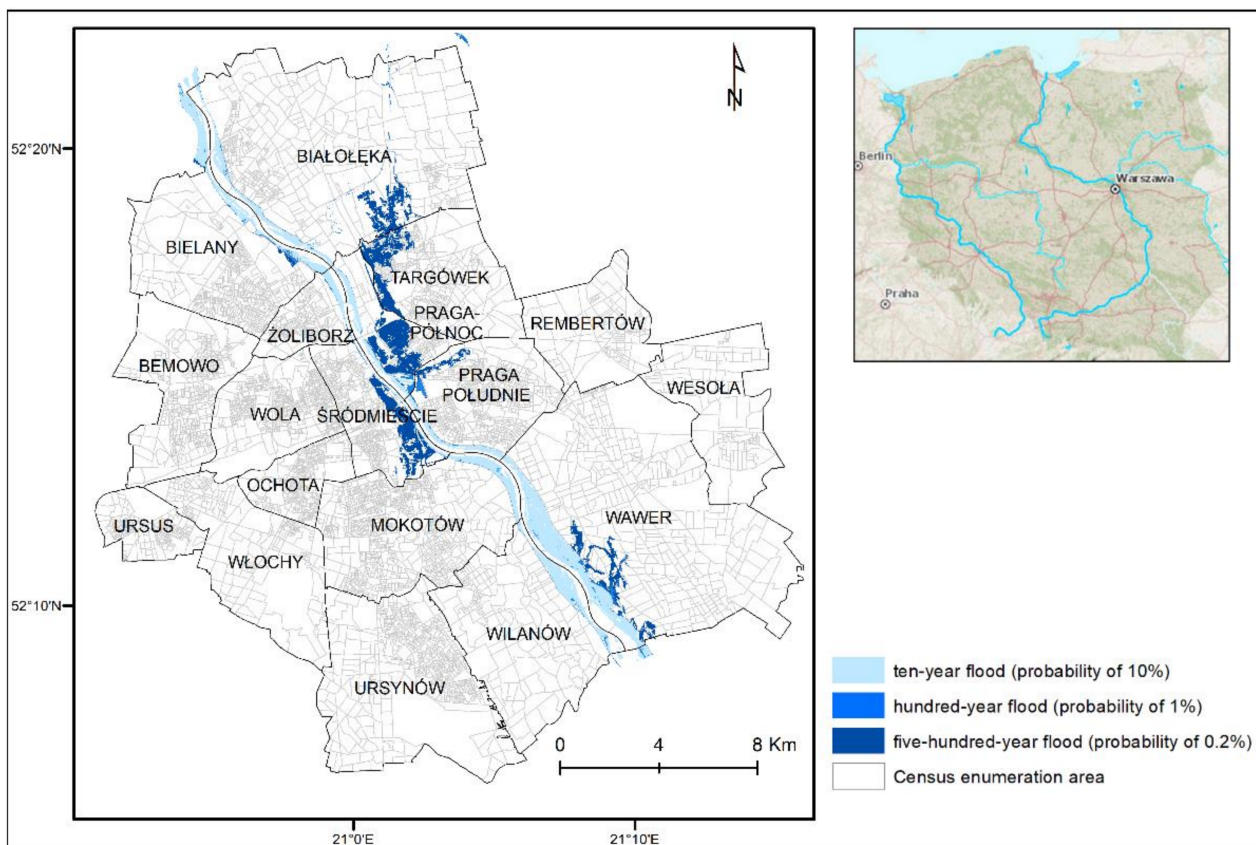
Poland, the central-eastern European country, suffers few natural hazards except for seasonal flooding, with a prevalence of early spring floods [1,29]. During the last 25 years, several countrywide initiatives have come into existence, amongst which the IT system of the Country's Protection Against Extreme Hazards (ISOK) is one of the major ones [37]. Pursuant to the Directive 2007/60/EC (the so-called Floods Directive) [38] the Polish flood protection ISOK provides all flood risk-management elements, i.e., prevention, protection, proper preparation and floods effects' removal. The potential flood effects relate to human life and health, the environment, cultural heritage, economic activity infrastructure and land cover [38–40]. The loss and damage assessment focuses on post-disaster losses, whereas the loss and damage risk refers to 'assessing the possibility and probability that some people in a community or nation will face severe loss and damage' and is a pre-disaster perspective [41]. Our approach is oriented toward the latter assessment. The common practice of expressing the impacts of flood events in monetary terms [42] can however distract from intangible impacts, the most important being the loss of life.

Our study focuses on the impact of floods on health of urban populations specifically those living in residential buildings in areas exposed to potential fluvial flooding. The aim of this study was to produce flood impact indicators to provide information on the conditions of residents, quantifying the magnitude of the flood impact on human health and to help identify areas of the highest risk to human health. Furthermore, this information can be used to increase public awareness of flood risks and to improve sustainable measures to minimise the impact of floods, for example by including flood risk as a design parameter for urban planning. The presented fluvial flood scenarios were developed by the State Water Holding 'Polish Waters', the national authority responsible for water management. In our approach, a residential building was adopted as the smallest spatial reference area unit. The urban population flood impact on building residents was defined and determined in relation to the following four factors: building capacity, building function, flood probability and flood depth. Our presented approach introduces the novel concept of building capacity and proposes its estimation method, an offshoot of the volumetric method. The remainder of the paper is structured as follows: Section 2 describes the study area, data and methods, Sections 3 and 4 describe and discuss the obtained results, respectively; Section 5 provides conclusions related to the developed research results.

## 2. Materials and Methods

### 2.1. Study Area and Data Used Description

The study area covers 27.11 km<sup>2</sup> and encompasses the Vistula River valley from ki-lometre 494.0 to 528.5 (Figure 1).



**Figure 1.** Warsaw, Poland, the flood risk zones.

The natural narrowing of the Vistula valley due to geological conditions was further limited by flood embankments created at the end of the 19th century and in the 1950s. Warsaw has been hit by floods many times. From the nineteenth century, catastrophic floods in the middle course of the Vistula occurred every few or several years (1813, 1838, 1839, 1844, 1845, 1855, 1867, 1884, 1889, 1891, 1903, 1924, 1947, 1960, 1962, 1997, 2010) and seriously affected Warsaw [29,43]. As noticed by [29,43,44] the Vistula River floods have generally been shaped by intensive rainfall in the Carpathian Mountains and rarely by snowmelt. Rainfall-induced floods occur mainly in June–July, while snowmelt—in March–April. Nowadays, 18.5 km left bank and 23 km right bank embankments, located mainly in the north and south part of the river course, protect the city against river inundation. The land cover structure in the Warsaw floodplains is diversified, in parts heavily urbanised and impervious but also covered by urban green areas, such as parks, garden, fruits, forest and bushes [45,46].

The study utilised several data sets listed in Table 1. All data sets are maintained by the public administration therefore they are highly reliable. As an element of the Polish spatial data infrastructure, they are free and publicly available through network services of the Polish Spatial Information Infrastructure Geoportal [47,48]. Flood risk zones with different probabilities of flood occurrence, namely 10-year flood (probability of 10%), 100-year flood (probability of 1%) and 500-year flood (probability of 0.2%), were estimated in the frame of the ISOK project. Flood risk zones were developed on the basis of mathematical-hydraulic MIKE11 models (2D or hybrid 1D/2D) for designing flood waves with different return periods (i.e., 500, 100 and 10 years) [37]. They constitute an indispensable element of flood hazard and flood risk maps, which provide comprehensive information to local authorities and the population, enabling planning of preventive and rescue actions during floods [49]. Flood risk zones were derived in vector format each zone patch is attributed with flooding depth in meters, the area of zone patches is given in square meter. According to the Floods Directive [38] flood risk zones are revised and updated every six years. The 10-year flood

zone covers an area of 14.38 km<sup>2</sup>, the 100-year flood spreads over 15.66 km<sup>2</sup>, while the 500-year flood—27.11 km<sup>2</sup>.

**Table 1.** Overview of data used.

Data Source Name	Object Type	Data Stakeholder	Spatial Resolution	Temporal
Flood risk zones	Flood risk zones	State Water Holding 'Polish Water'	1:10,000 [m] <sup>1</sup>	2016–2021
Topographic data (BDOT10k)	Buildings	Surveyor General	1:10,000 [m] <sup>2</sup>	2012; 2018–2019
Territorial Division	Census enumeration area	Surveyor General	1:10,000 [m] <sup>1</sup>	2019
Population	Population counts	Central Statistical Office	Census enumeration areas	2011
Housing economy and municipal	Average usable area of dwellings	Central Statistical Office	Warsaw districts	2000–2019
Infrastructure, Housing stocks	Average number of persons dwelling	Central Statistical Office	Warsaw districts	2000–2019

<sup>1,2</sup> The data is available in the vector shapefile format, the accuracy of the horizontal position amounts to 6 m [37], 1 m [48], respectively

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The Polish topographic data (BDOT10k), a national vector database with a thematic scope and a level of detail corresponding to civilian topographic maps at a scale of 1:10,000, was the source for the buildings data layer. Buildings' location and characteristics are derived from the cadastre. Buildings' footprint areas expressed in square meters, their function and the number of storeys, are all crucial for this research.

The census enumeration area (also referred to as EA) is the smallest spatial statistical unit defined for censuses and other statistical surveys according to the number of flats and inhabitants, amounting to not more than 500 persons and 200 dwellings. Boundaries of census enumeration areas are adjusted to the administrative division and consistent with the units used in the cadastre. Moreover, census enumeration boundaries are spatially adjacent to the boundaries of towns or settlements [50]. In this case, 532 census enumeration areas covered the studied region, the area of the smallest census unit amounted to 0.11 ha, and the largest to 98.32 ha. In 2011, according to the national census, twelve census EAs were uninhabited, while in five—the number of people exceeded 500. Most, as many as 939 people, lived in an EA unit of 6.46 ha. Statistical data on population, average usable area of a dwelling, and the average number of persons per dwelling was obtained from the Local Data Bank provided by the Central Statistical Office [51].

## 2.2. Method Applied

Flood risk maps visualise the levels of expected losses i.e., the magnitude and nature of the risk, during a particular time period, as a result of a particular flood event. In contrast to hazard maps, risk maps quantify economic losses, mostly directly expressed as a monetary value. The flood risk maps show the indicative number of persons at risk in an assumed spatial reference area as the population number within this area. Nevertheless, this information is blurred due to the vast informational and thematic scope of the maps and, more importantly, it is not detailed due to the generalised manner of the population distribution portrayal and the spatial incongruity [52]. Consequently, our research goal was

to improve the level of detail and thematic scope of information about the potential risk impact of flooding on the human population. This issue was addressed by estimating the urban population at the building level and redefining the urban population flood impact on building residents.

In order to accomplish this study goal, the basic assumptions were as follows:

1. A flood-occurrence probability ( $p_{Qi}$ ) amounts to 10%, 1%, 0.2% for high, moderate and low probability floods, correspondingly.
2. A flood scenario is characterised by the floodwater level. This factor also implicates the flood horizontal extent, i.e., area prone to flooding.
3. One building is the smallest spatial reference unit.
4. A building's occupant capacity (hereinafter referred to as building capacity and denoted as  $b_{cap}$ ) was introduced and defined as the number of permanent residents of any type of residential building or hotel.

The limitation of analysis to residential buildings and hotels is justified in the national [39,40], and EU regulations [38] related to floods and flood hazards. The residential building category (denoted further as  $b_c$ ) comprises of a single-family building, two-family building, multi-family building (i.e., three or more family building), hotel, monastery as well other houses of permanent residence, i.e., children's home, student dorm, workers' hostel, boarding-school house, homeless shelter. The adopted methodology is based mainly on GIS and cartographic modelling and uses the overlay and spatial relations functions, which are commonly used in flood risk modelling [10,18–20,22].

To analyse the urban population flood impacts based on flood forecasts, flood risk modelling is of great importance. Usually, either a deterministic or stochastic approach is used. Deterministic models identify hazards and exposure outputs in vulnerability analyses, but their limitation is that they do not calculate risk. In contrast, probabilistic models provide information on the amount of risk. Hence, deterministic models used in conjunction with probabilistic models can be used for more detailed threat modelling, which unfortunately is not the standard, in the context of applied practice [53].

Inspired by the above [53], a dual approach was also followed. The expected impact of flooding was defined in the aspect of risk to urban population health and life as the expected value of the cost of flooding, i.e., the sum of the product of the probability of an event  $p_{Qi}$  and its cost, expressed by the number of inhabitants (of the building)  $b_{cap}$  (Equation (1)). This measure is stochastic in nature.

$$Im_{stoch} = \sum_{i=1}^n b_{cap} * p_{Qi}, \quad (1)$$

If the chance of occurrence of the flood event is ignored, it is still possible to identify flood hazard and exposure. Therefore, a measure of the deterministic impact of flooding in terms of risk to human health and life was defined as the product of the building capacity  $b_{cap}$  and a damage function  $f(h, b_f)$  that depends on two variables, i.e., flood water level  $h$  and building function  $b_f$  (Equation (2)).

$$Im_{determ} = b_{cap} * f(h, b_f), \quad (2)$$

The term 'function' refers to the purpose of a building, e.g., commercial, office, residential or even farm livestock. The values of the damage function for land use classes and water depth ranges were defined by the National Water Management Authority within the framework of the system for the Country's Protection Against Extreme Hazards. The residential land use takes values as follows (Table 2).

**Table 2.** The values of the damage function for residential land use (here:  $b_f$  is constant and equals ‘residential’).

Water Level $h$ [m]	Damage Function $f(h, b_f)$ [%]
$h \leq 0.5$	20
$0.5 < h \leq 2$	35
$2 < h \leq 4$	60
$h > 4$	95

Finally, the combined flood impact was defined as the geometric mean of the stochastic and deterministic nature impacts, which we later refer to as  $Im_{comb}$  (Equation (3)).

$$Im_{comb} = \sqrt{Im_{stoch} * Im_{determ}}, \quad (3)$$

The impact measures, i.e.,  $Im_{stoch}$ ,  $Im_{determ}$  and  $Im_{comb}$  express the number of a building’s residents whose lives and health would be affected by a flood in a pre-modelled scenario, in the stochastic, deterministic and both aspects, respectively.

Modelling of the building’s capacity  $b_{cap}$  assumes a relationship between the number of people staying in a residential building and its volumetric characteristic. The proposed approach is a further development of the model defined by [54]. It considers all houses of permanent residence, that is family buildings, children’s homes, student dormitories, workers’ hostels, boarding-school houses and homeless shelters. Another important factor increasing the accuracy of modelling the number of people in a building is the reduction of the total building footprint area to the total usable space. Hence, the main assumptions were as follows: A single-family house is inhabited by the statistical average number of people ( $Pd$ ) provided by the Central Statistical Office (the average occupancy rate per household), while in case of a two-family house this number is multiplied by two. To estimate the number of people in multi-family buildings and other houses of permanent residence (see Table 3), the number of dwelling (or rooms, in case of hotel- or hostel-like buildings) are additionally considered, based on the number of storeys ( $Ns$ ), the building footprint area ( $Ab$ ) reduced to the total usable space using Ari coefficient and the dwelling (or room) average area. The total building capacity is calculated by multiplying the number of dwellings (or rooms) by the average number of person ( $Pd$ ). In case of hotels, the occupancy rate ( $Oh$ ) is also considered. The building capacity was computed using Python scripts according to Equation (4).

$$b_{cap}(f) = \begin{cases} Pd_i, & \text{for } b_c = 1 \\ 2Pd_i, & \text{for } b_c = 2 \\ Ns * \left(\frac{Ar_i * Ab}{Da_i}\right) * Pd_i, & \text{for } b_c = 3 \\ Ns * \left(\frac{Ar_i * Ab}{Da_i}\right) * Pd_i * Oh, & \text{for } b_c = 4 \\ Ns * \left(\frac{Ar_i * Ab}{Da_i}\right) * Pd_i, & \text{for } b_c = 5 \\ Ns * \left(\frac{Ar_i * Ab}{Da_i}\right) * Pd_i, & \text{for } b_c = 6 \end{cases} \quad (4)$$

where:  $b_c$ —residential building category,  $Pd_i$ —average number of persons per dwelling,  $Ns$ —number of storeys,  $Ab$ —area of a building’s footprint in square meters,  $Ar_i$ —coefficient of building footprint area reduction,  $Da_i$ —average usable area of dwelling in square meters,  $Oh$ —occupancy rate of hotel rooms. The category of a building  $b_c$  takes the value: 1—for a single-family building, 2—for a two-family building, 3—for a multi-family building, 4—for a hotel, 5—a monastery and parish house and 6—other houses of permanent residence.



**Table 3.** The adopted values of coefficients used for building capacity calculation.

Building Function ( $b_f$ ) Name	$b_f$ Value	$Da_i$ [ $m^2$ ]	$Pd_i$	$Ar_i$	$Oh$
Single-family building	1		2.3		
Two-family building	2		2.3		
Multi-family building	3	59	2.3	0.75	
Hotel	4	18.5	1.5	0.70	0.75
Monastery and parish house	5	15	1.0	0.50	
Other houses of permanent residence (i.e., children's home, student dorm, workers' hostel, boarding-school house, social care home, homeless shelter)	6	10	2	0.65	

The analysis used 10-year mean values of the  $Pd_i$ ,  $Da_i$  and  $Oh$  coefficients (Table 3) calculated from the statistical data for 2010–2019, while  $Ar_i$  was adopted on the basis of opinion of experts in the field.

The implemented coefficients for family buildings were verified by summing up the number of inhabitants in those residential building in the year 2012 located within the census enumeration area and comparing the estimated number of inhabitants with the 2011 census data. The accuracy of population estimation was 2%.

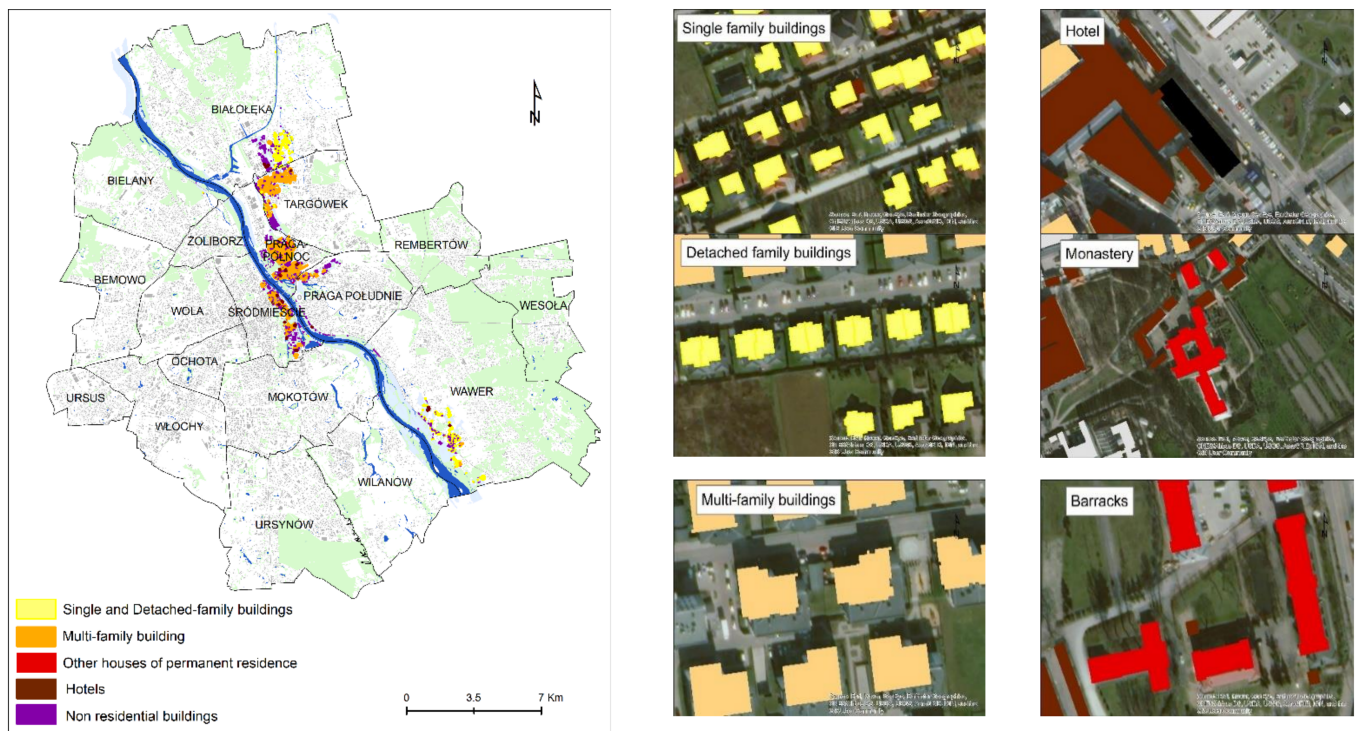
### 3. Results

Out of the total 156,907 buildings located in Warsaw in the year 2019, 3693 (2.35%) are situated within the 500-year flood hazard zone. Slightly more than half (50.8%) of the buildings in the flood hazard zone comprise residential buildings, including, among others, 642 single-family buildings, two semi-detached family houses, 1184 multi-family buildings and 20 hotels (see Table 4). Single-family houses, clustered linearly, are mainly located on the right-bank of Warsaw, in the fringe districts Wawer (on the south) and Białołęka, the norther district. Detached houses are scattered around the northern and southern Warsaw districts, usually in the near vicinity of single-family housing.

**Table 4.** Buildings and people in the floods risk zone.

Building's Type	Number of Buildings			Total Building's Occupant Capacity		
	500-Year Flood	100-Year Flood	10-Year Flood	500-Year Flood	100-Year Flood	10-Year flood
Single-family building	642	6	0	1478	14	0
Two-family building	2	0	0	9	0	0
Multi-family building	1184	0	0	111,292	0	0
Hotel	20	1	0	4233	57	0
Monastery and parish house	18	0	0	1096	0	0
Other houses of permanent residence	21	3	0	4761	262	0
Other non-residential buildings	1807	98	50	0	0	0
All buildings	3693	108	50	—	—	—
Total number of people	—	—	—	122,869	333	0

Multi-family buildings are concentrated in the city center, namely Śródmieście (20%) and Praga Północ (32.6%), and in Targówek (17.7%). They form housing estates separated by urban greenery and streets; however, several are isolated between buildings of a different type, i.e., office and service premises (see Figure 2). The spatial distribution of people (residents and hotel guests) exposed to the risk of flooding corresponds to the location of residential buildings. In total, 122,869 people may be affected by the 500-year flood and 90.57% of them lived in multi-family houses, i.e., the multifamily building capacity equals 111,292 (see Table 3). Most people at risk of flooding live in Praga Północ (44.6%), Śródmieście (27.1%) and Targówek (20.8%).



**Figure 2.** Warsaw, buildings in the 500 flood risk zone.

As shown in Figure 3 (the red color), the percentage of people at risk in the census enumeration areas including multi-family housing may reach even 100% and does not fall below 91%. Among people staying in houses of permanent residence (children's home, student dorm, workers' hostel, boarding-school house, social care home, homeless shelter, barracks) 4761 are exposed to the risk of flooding. On the other hand, the number of hotel guests staying in hotels located within the 500-years flood risk zone can slightly exceed 4200 people. These hotels are mainly located in the central city districts (see Figure 2). Just over a thousand people live permanently in monasteries and parish houses located in the central part of Warsaw, both on the left and right banks of the river.

Only 108 buildings are situated in the 1% risk zone (100-year flood), including six single-family houses, one hotel, three workers' hostels, most of them are located on the right bank of the Vistula, in Wawer (35%), Praga Południe (38%) and Praga Północ (15.7%). Their total capacity amounts to 333 people. The highest building capacity value, as many as 262 residents, is assigned to workers' hostels, while the average building capacity of the Wisetka Hotel equals to 57 people.

The most likely 10-year flood does not affect people staying in residential buildings, because its spatial extent is limited mainly to the Vistula riverbed (see Table 4).

Apart from function, capacity or the number of floors, a building can be characterised by the impact of a flood on its residents, where the higher the value, the more people whose lives and health would be affected by a flood in a pre-modelled scenario. Within the test area, the stochastic, deterministic and combined impacts of the flood on the building's residents range from 0 to 2.8 persons, from 0 to 482.4 persons and from 0 to 36.5 persons, respectively (Table 5).

Buildings located in the flood hazard zone have been classified according to the impact of river flooding, using Natural Break classification method (Table 5, Figure 4). As noted by Jenks [55] Natural Break classification method reduces the variance within classes and maximises the variance between classes. The classes have been assigned colours (Figure 4), which the map reader intuitively associates with the level of risk or flood impact (red—high, yellow—medium, green—low).

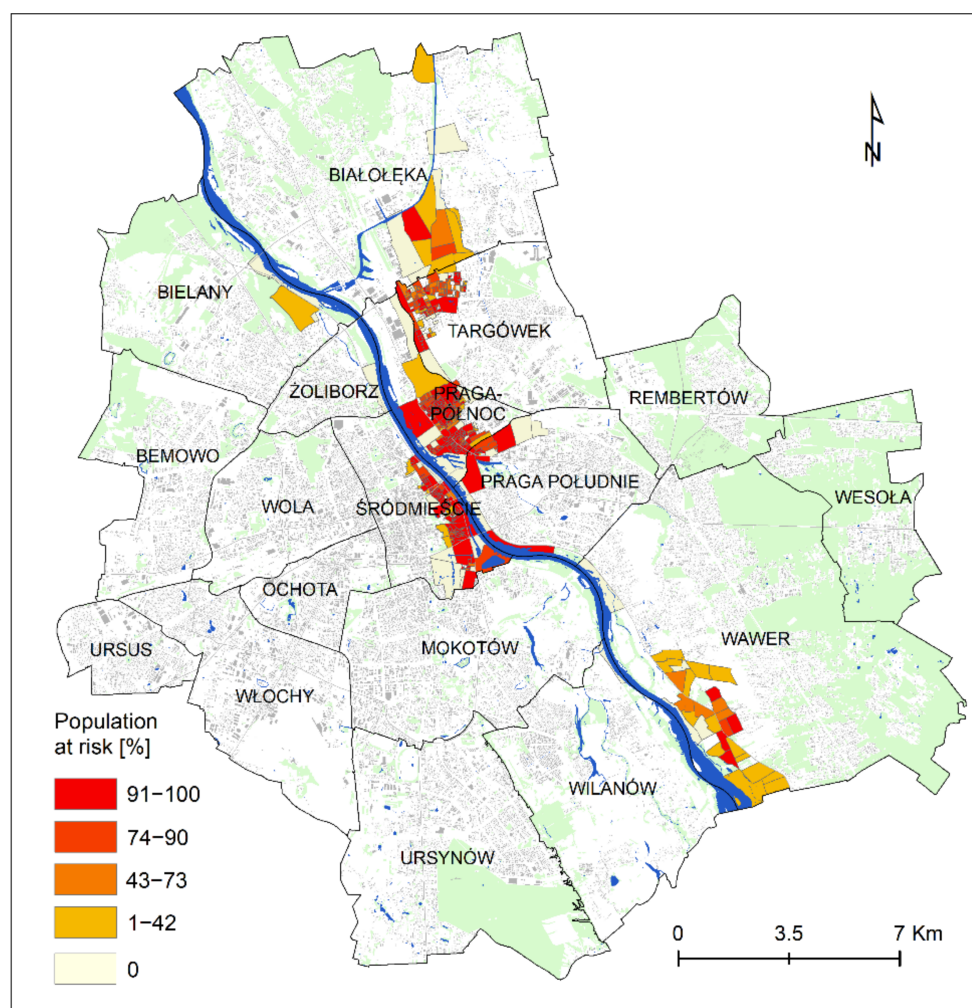
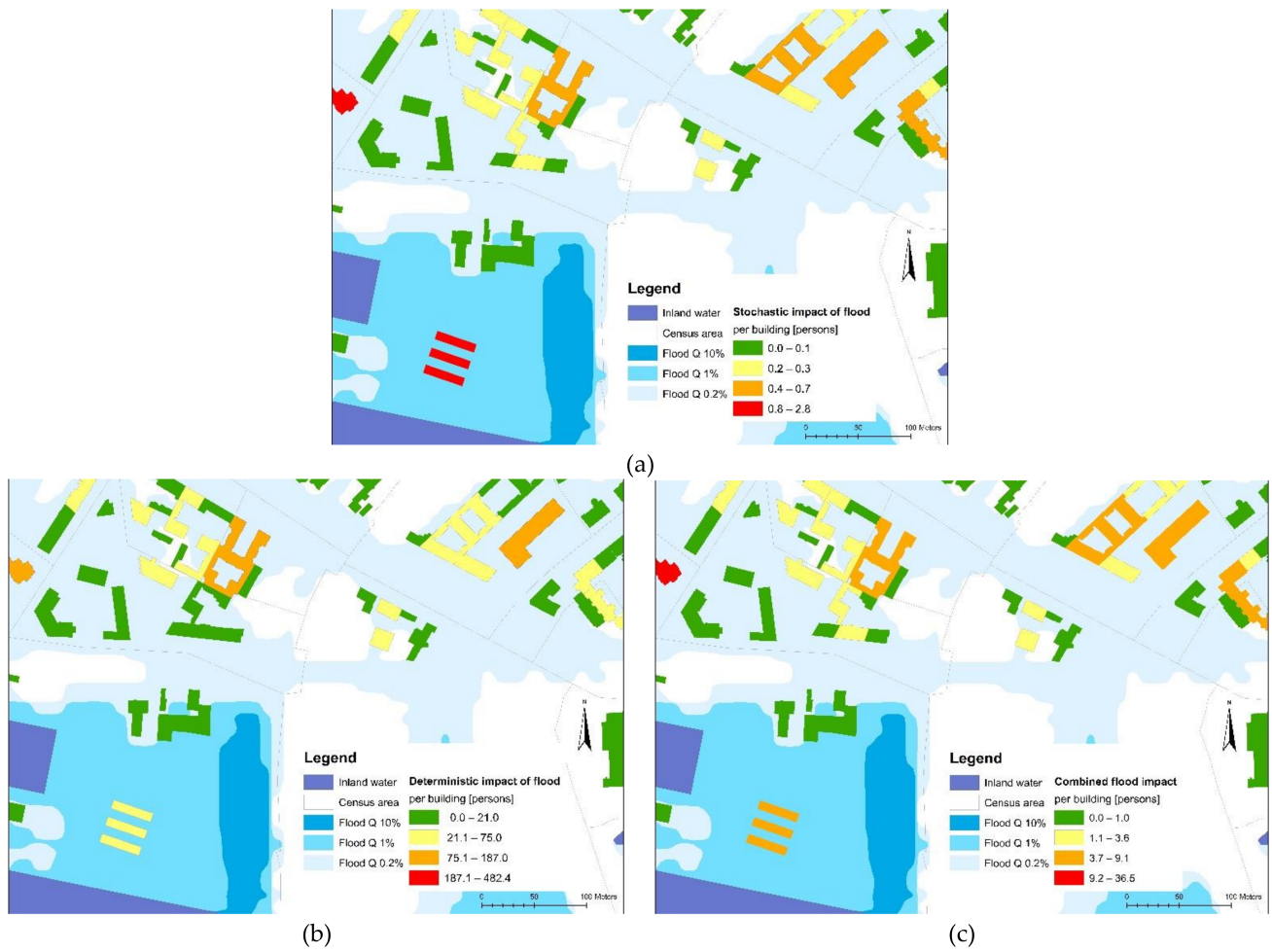


Figure 3. Warsaw population at risk, percentage of people attributed to the census enumeration areas.

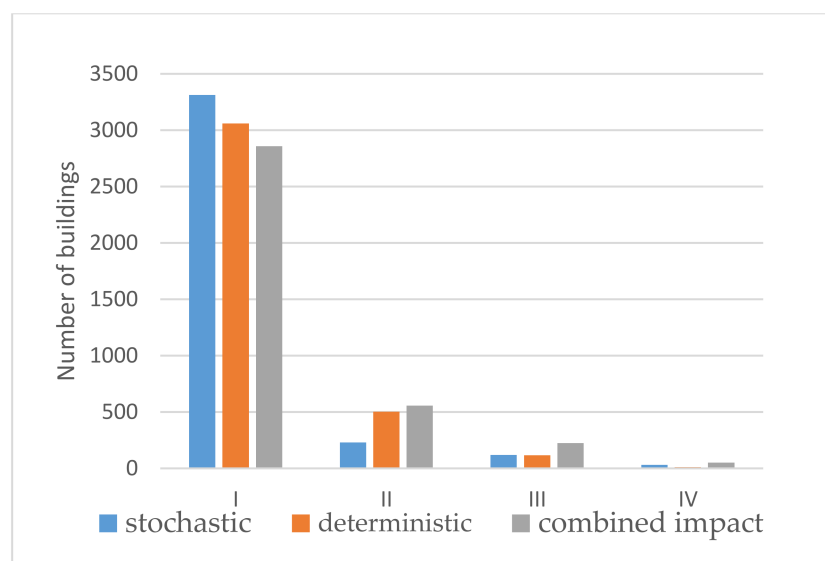
Table 5. The percentage of buildings within the classes of the stochastic, deterministic and combined impacts of flooding attributed to buildings.

Flood Impact Class	Stochastic		Deterministic		Combined	
	Class Range	% of Buildings	Class Range	% of Buildings	Class Range	% of Buildings
I (low)	0.0–0.1	89.7	0.0–21.0	82.9	0.0–1.0	77.4
II (medium)	0.2–0.3	6.2	21.1–75.0	13.6	1.1–3.6	15.1
III (high)	0.4–0.7	3.2	75.1–187.0	3.2	3.7–9.1	6.1
IV (very high)	0.8–2.8	0.8	187.1–482.4	0.3	9.2–36.5	1.4
mean	0.07	n/a	11.9	n/a	0.89	n/a

The differences between the three defined impacts values are apparent within a selected sample area where different buildings belong to different flood scenario zones (as in Figure 4). In Warsaw, the number of buildings characterised by a very high flood impact equals 30, 11 or 52 for stochastic, deterministic or total impact, respectively, provided the Natural Breaks classification method is used (Figure 5).



**Figure 4.** Residents whose lives and health would be affected by a flood in a pre-modelled scenario, in the stochastic (a), deterministic (b) or both aspects (c), attributed to building.

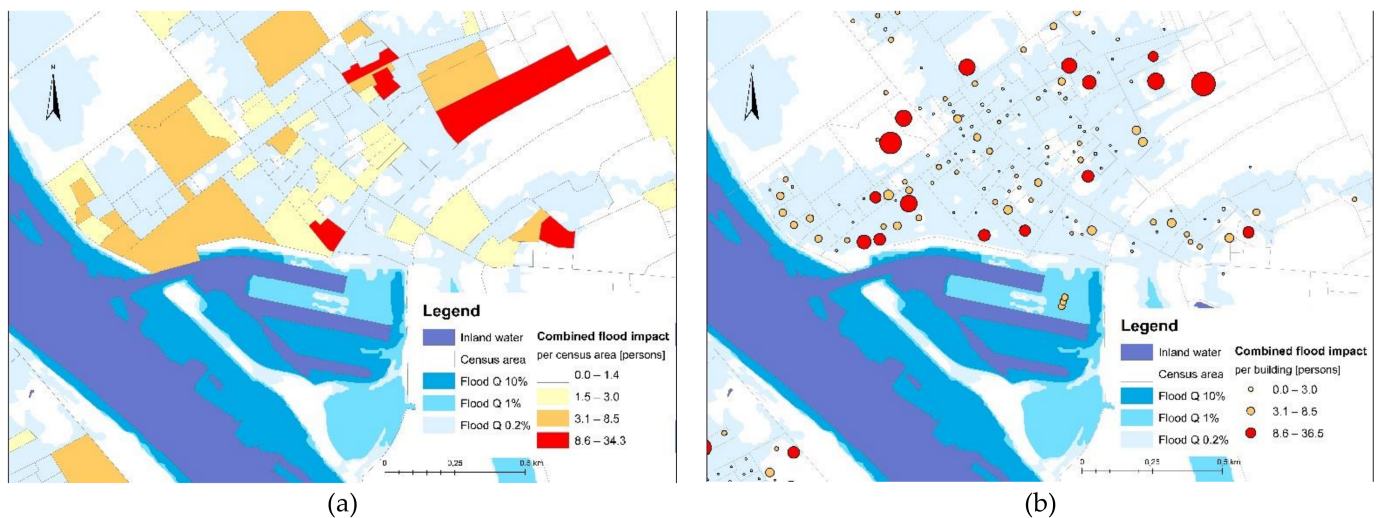


**Figure 5.** The values of the stochastic, deterministic and combined flood impacts on building residents within classes representing impact levels within Warsaw, Poland. The higher the class number (I, II, III, IV) the higher the impact.



The results show that over 122,000 residents live in the areas that may be affected by 500-year flood. However, the foreseen magnitude of flood impact on human health is moderate, i.e., on average ten persons per residential building over the 80% of flood risk zones. Such results are attributed to the low inundation depth, i.e., below 1 m.

The classes of combined flood impact attributed to a census enumeration area, defined as the mean (building) impact per census area, are presented in Figure 6a. The class with the highest combined impact of flooding attributed to a census area is coloured in red. Figure 6b illustrates the classes of the combined impact of flooding attributed to a building delineated as a point (i.e., building polygon weighted centre). The signatures with variable size, also referred to as quantitative signatures, were chosen to visualise the impact. The red dot applies to the highest combined impact of flooding attributed to the building.



**Figure 6.** The combined impacts of flooding attributed to a census enumeration area, selected samples of the Warsaw flood risk zone, visualised by (a) quantitative method, (b) qualitative method, variable size signatures.

The spatial distribution of the members of classes with the highest combined impact of flooding does not depend on the distance to the river. Instead, it reflects the terrain height and the distribution of the different building classes and their residents' number.

## 4. Discussion

### 4.1. Building Capacity

The building-level population represents a very high level of detail of population data, valuable for micro-scale spatial analyses (compare [56]). An example of such an analysis is a study examining the impact of potential flooding on building inhabitants. Due to the detailed population data sensitivity and consequent unavailability, scientists often downscale the global population raster product, available at 30" resolution, using OpenStreetMap (OSM) or buildings extracted from remotely sensed data (eg, satellite imagery or LIDAR data). Birkmann and Welle [41] exploited the Global Rural-Urban Mapping Project (GRUMP) to assess people affected by natural hazard events, including floods, using a modified WorldRiskIndex. Similarly, the World Risk Index was adopted by [57] to estimate levels of flood exposure, vulnerability and risk in Brazil. To determine the number of people at risk, the authors used LandScan, the global population raster data. Zhu et al. [25] estimated the building-scale population distribution by downscaling Asia WordPop using POIs OSM data and the results obtained were generally consistent with WorldPop data on a macroscopic level ( $R^2$  of 0.86). The global raster population data (GRUMP, LandScan, GHS-POP), however, tends to underestimate people counts in densely populated areas as well as in the transition areas between urban and rural, while overestimation was observed along main roads and in city centres [58–60].



With the advancement of remote sensing technologies, such as LIDAR, aerial and satellite imaging [61–63], it is possible to automatically and remotely measure footprint and height (or volume) of a building, however, obtaining information about the function of a building using this procedure is limited.

In this paper, a quick method to estimate a building capacity, i.e., building-level population in residential buildings and hotels, is proposed and implemented. The method can be classified as an offshoot of the volumetric method for a building population estimation (compare [64], except that it (a) requires detailed information on building types and their number of storeys (available for the whole of Poland), and (b) modifies the building volume based on this information. The effects of tourism (except from hotel occupancy rate), day- and night-time populations were not considered.

#### 4.2. Impact of Flooding on Building's Residents

The EU Floods Directive [38] has left to the Member States, much flexibility on measures. This also applies to the assessment of the potential adverse consequences to human health. Therefore, there is a number of non-mutually exclusive approaches, their results, however, are not harmonised and thus non-comparable.

Flood damage is prevalently shown as total monetary building replacement cost [28,65] or as the number of buildings at risk [18]. Given the significant differences in the buildings considered (e.g., all residential buildings [28]; only single-family residential buildings [65]; buildings of any types [66]; residential and commercial buildings [18,28]) as well as the changes in costs depending on the geographic location of the building and the valuation date, the monetary values described in the literature are incomparable [28,67].

Regarding the defined in this study measures of the impact of flooding on building residents, it is easy to notice that the characterisation of potential losses by the expected value of the cost of flooding results in low numerical values, hence low stochastic impact values. Moreover, irresponsible (i.e., without knowledge of its interpretation) use of such an indicator, which carries information about the rare occurrence of floods, may negatively affect the awareness of flood risks among the public (inhabitants or even members of the local administration). Other worth emphasising features of the stochastic and deterministic flood impacts are their incommensurability and, to some extent, independence. Considering all three of the above-mentioned characteristics, it was somewhat challenging to fairly and correctly include both component influences in the introduced composite flood impact on building residents. To harmonise the two component impacts, their joint impact is described by their geometric mean and expresses the number of people whose health or life would be affected by the flood.

Large variations in the values of the predicted combined impact of flooding on building residents are also readily apparent. This applies both to the large scale, i.e., the level of detail of small administrative units (Warsaw census districts, average area of about 0.25 ha), and to the very large scale, i.e., the level of detail of the building. Similar variation characterises the other measures of flood impact. Such a feature is useful, allowing the classification of buildings based on impact values and consequently also the classification of census enumeration areas.

Regarding the issue of uncertainty of our approach, this is a very complex problem since the total uncertainty is a function of uncertainties of individual factors, such as data sources, data processing methods and error propagation. Models adopted at the different stages of the overall framework, e.g., hydro-modelling method, loss function, contribute to the flood impact uncertainty together with the positional and thematic accuracy of input vector data (e.g., floodplains, buildings). Another bottleneck is these uncertainties accumulations and propagation model. Therefore, the verification of the obtained results, as well as the uncertainty of the assessment of flood losses in buildings and people, was limited to the number of people assigned to the building, i.e., building's capacity.

The developed method slightly overestimated the number of people in the census EAs. The estimates lie 2% above the reference data values. Such a result contributes to the

high reliability of the method. It is a kind of unbiased population estimation approach. Moreover, the building's residents' estimation method performed well despite choosing a study area characterised by a high diversity of buildings, in terms of their function, size, density and rapid change rate.

#### 4.3. Flood Impact Cartographic Visualisation

An adequately selected method of cartographic presentation for a studied phenomenon or indicator positively influences the interpretation of statistical relationships. There are studies (e.g., [68]) that their practical interpretation, in the context of flood risk, is supported by a wider use of qualitative methods. A range of qualitative as well as quantitative methods can be found among the methods of presenting phenomena on maps. Consequently, the cartographic visualisation of the impact of flooding can be an important, valuable and effective tool for risk communication.

The choice of both the method of impact values classification and the method of results presentation, e.g., using the cartographic visualisation, is of great importance as they should facilitate the interpretation of results, and also support the prioritisation of sub-areas within a study area, e.g., according to the magnitude of evacuation demand. Any administrative subdivision (e.g., districts, municipalities) or a special one, e.g., census tracts may serve as a spatial reference unit (sub-areas). In our example (Figure 6), the visualisation of the effects of the large-scale analyses includes the option of taking a building as the smallest spatial reference unit, while the smaller-scale visualisation includes census tracts.

## 5. Conclusions

As the most valuable resource, people should be targeted for special protection. The proposed new indicators can be used in every phase of the disaster life cycle, whether in investment planning, evacuation planning or educating the public to raise awareness of flood risks and their impact. Detailed information on the distribution of the population and a rapid method of obtaining indicators of the impact of flooding on this population provides a tool to support real-time crisis management in the event of an occurrence of such a hazard. In such a case, the most appropriate indicator is the deterministic flood impact. In contrast, the combined risk, carrying the deterministic and stochastic aspects, contributes to determining the regions with the greatest need for measures to mitigate the potential impacts of flooding on human health (where the higher the indicators, the greater the need) and, subsequently, facilitate to target and prioritise such measures.

The population data estimation at the (residential) building level, i.e., at the virtually highest level of detail, enables GIS analyses at any scale. For flood scenario analyses at the micro-scale is very useful, while for decision support purposes the cartographic visualisations at meso scale (achievable by dedicated generalisation of micro scale results) can be an asset.

Absolute protection against flooding, a natural severe weather phenomenon, is not achievable [69]. The continuous improvement of detailed analyses of different flood scenarios, however, including the use of the flood impact indicators proposed here, as well as their clear cartographic presentation for both decision-makers and inhabitants, contribute to effective mitigation and even protection against the false sense of security.

Our research will continue on this topic through uncertainty quantification analysis and the alternative design of the flood impact cartographic visualisations to help maximise the message comprehension independently of readers abilities or access to technology.

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