1. Introduction

The global increase in air temperature arouses widespread social interest because its effects are felt worldwide – particularly in the Northern Hemisphere. Climate change affects the functioning of the Earth System in many ways, including changes in the intensity of hydrological and morphogenetic processes that result in transformation of landforms. Climate change activates a positive feedback loop characterised by accelerated changes in environmental conditions, and morphogenetic factors and processes. Understanding the impact of current global climate change on the evolution of landforms and landscapes is, therefore, one of the critical challenges for geomorphology (Guerreiro et al., 2018; Harrison et al., 2019; Knight & Harrison, 2012, 2013; Lane, 2013; Naylor et al., 2017; Spencer et al., 2018; Spencer & Lane, 2017; Zwołiński, 2011). This understanding is essential for policy and resource management. The top five hazards faced by cities worldwide are flash/surface flooding, heat waves, rain storms, extreme hot days, and droughts (CDP, 2021). The causes, course, and effects of global warming have significant consequences for future landform dynamics in natural and urban areas, at shorter and longer timescales (IPCC, 2018, 2019). In Poland, global warming induces changes in precipitation (Kożuchowski & Żmudzka, 2003; Ziernicka-Wojtaszek, 2006), an increase in the frequency of strong winds (Araźni & Lorenc, 2007; Lorenc, 2005), and sea-level rise (Kundzewicz, 2008; Rotnicki, 2009; Wiśniewski et al., 2011). In the present context of climate change, new investigations and action plans are needed for enhancing this valuable urban geomorphological heritage and protecting it from both natural hazards and anthropogenic activities (Bollati et al., 2015; Brandolini et al., 2019, 2020; Faccini et al., 2020; Reynard et al., 2017).

The most common sequences of extreme events such as forcing-response processes include meteorological cause -> geomorphological effect, and meteorological cause -> hydrological phenomenon -> geomorphological effect (Fryirs, 2016; Zwołiński, 2011). These sequences are often catastrophic and cause many changes in the environment and human activity. Denudation of the earth’s surface by water and wind is a significant geomorphic process in every area of the world. This process, however, is very difficult to quantify (Fenta et al., 2020; Gibbs & Salmon, 2015). The estimation of land denudation rates in urban areas is particularly challenging due to the lack of direct field and experimental evidence. One solution to this problem is mapping the land degradation risk. The ongoing climate change, which increases the risk of extreme events, requires action to mitigate its potential impact on the urban landscape and ensure the safety of human communities (Contreras et al., 2020). Extreme events are a particular challenge for cities: these events are magnified by urban effects such as anthropogenic changes.

ABSTRACT

This paper presents the results of geohazards mapping and evaluation their role in the modifying of the urban landscape in Poznań, Poland. Information on geohazards specific to an urban lowland area (river floods, flash floods, mass movement, wind erosion) because of increasing climate change was compiled into a geomorphological map. The most spatially widespread geohazards in Poznań include: (a) on moraine hills/uplands: mass movement, wind erosion, and flash floods (9.9% of the city area); (b) on outwash plains: mass movement and flash floods (8.6% of the city area); (c) on fluvioglacial landforms: mass movement and river floods (9.8% of the city area); (d) within plains of various origin: flash floods (7.6% of the city area). Mass movement affecting short but numerous (and locally steep) slopes, and flash floods are the most widespread geohazards (16 and 14%, of Poznań’s area, respectively). Extensive urbanisation especially the expansion of impervious surfaces increases the high risk of flash floods.

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in landforms, land cover and land use, the water cycle, geodiversity, and biodiversity (Galderisi & Ferrara, 2012; Grimm et al., 2008). Since the majority of Poland’s population live in urban centres, and this urban population is increasing, cities and towns are priority areas for geohazard risk assessment and mitigation.

Notwithstanding their fundamental importance for practical applications, urban geohazard maps present substantive and editorial challenges (Capes & Teseu, 2017; Chaminé et al., 2016; Grivei et al., 2018; Lyu et al., 2018; Mateos et al., 2017; McCall, 1998; Smith & Rosenbaum, 1998). The studies of urban geohazard maps are relatively few, primarily due to the limited extent of comprehensive monitoring and detailed field study of current morphogenetic processes in urban areas. These processes are subject to constant changes due to the construction of anthropogenic landforms, sealing of the ground surface, changes in rainwater runoff, etc. Examples of geohazard maps of specific cities can be found in the studies by Kaphle et al. (2007), Vecchiotti and Kociu (2013a, 2013b), Cigna et al. (2015), Hofmann et al. (2017), Eremina et al. (2018), Paliaga et al. (2019), and Totaro et al. (2020). More commonly, however, geohazard maps are made for regions rather than cities (e.g. Al-Kouri et al., 2013; Dragičević et al., 2011; Faccini et al., 2020; Kusky et al., 2010; Lyu et al., 2018; Mandarino et al., 2021; Pitidis et al., 2018; Wotchoko et al., 2016). Moreover, most geohazard maps are limited to selected processes – mainly mass movement and flooding (EGDI, 2019; Guzzetti, 2019; Monserrat & Barra, 2019).

In this study, field mapping, geoinformation analysis, and a literature survey let us identify and mapping of geohazards in the Poznań urban area. The final map of Poznań with spatial distribution of geohazards associated with river flooding, flash floods, slope-instability processes and deflation is presented on the background of general geomorphological setting. This map aims on the one hand at increasing the awareness of citizens on geohazards prevention and on the other hand it should provide useful information for spatial planning, land management and risk assessment. A joint geohazards map for an area with a complex morphology and a high degree of urbanisation allows the assessment of the relationship between different provenance of geohazards and between them and residents and urban infrastructure (Terranova et al., 2018). This type of mapping is an important tool for decision makers to plan and for adopting the more adequate activities for risk mitigation and reduction (Di Salvo et al., 2017; Nicu, 2017; Paliaga et al., 2019).

2. Study area

Poznań, one of Poland’s largest cities (area: 261.9 km²), is the economic, administrative, and industrial centre of the Wielkopolska region, and a crucial transport junction (Figure 1A). On 31st December 2020, the city accounts 532,048 inhabitants (USwP, 2021). Poznań is located in the Wielkopolskie Lake District, which is part of the Central European Lowlands. Poznań’s landforms have resulted from Pleistocene–Holocene morphogenesis. The regional landscape was significantly influenced by glacial and glaciofluvial processes during the Weichselian glaciation (Zwoliński et al., 2008). Significant areas in Poznań are flat, outwash plains and ground moraine plateaus (mainly 80–100 m a.s.l.) with a slope of 0–0.5°, transitioning into moraine hills with the steepest slopes of 8–16° (Figure 1B,C, Hildebrandt-Radke, 2016), in the north of the city. The highest hill is Moraska Góra (154 m a.s.l.). Erosive landforms, such as glacial channels, river valleys, and endorheic depressions, diversify the surface of plateaus and outwash plains. Other landforms in Poznań include eskers, kames, marginal lake plains, and numerous anthropogenic forms. The lowest-lying area is the bottom of the Warta River valley (48.8 m a.s.l.). The valley is incised in the moraine plateau at a depth of 20–40 m; the length of the river section within the city limits is 15 km. Seven discontinuous terrace levels of Late Glacial to Holocene age are present in the valley (Bartkowski, 1957). The valley floor is filled with gravel, sand, mud, and Holocene peat (Figure 1C; Chmal, 1996). The Warta River is fed by snow and rain, with one major snowmelt or ice jam flood in the spring (February–April) and rainfall-induced floods being more frequent in the summer. The average annual flow of the Warta River in Poznań is 107 m³ s⁻¹ (Wrzesiński & Perz, 2020).

The hydrographic network was a decisive factor for the location of the city (Kaniecki, 2013; Makohonienko et al., 2016). The initial site of Poznań, at the end of the tenth century CE, was the river islands on the Warta River floodplain. Medieval Poznań was built on the second left-bank meadow terrace, in 1253 CE (Kočka-Krenz, 2015). Poznań’s urban landscape has changed many times since the Middle Ages due to human intervention, first on the relief of the Warta River valley floor, later on the meadow terraces and moraine plateau. These interventions have given rise to an extensive inventory of anthropogenic landforms and sediments (Zwoliński et al., 2017). Green areas, including forest, grassland, and recreation and arable areas, cover approximately 50.9% of Poznań (Figure 1D). Agricultural land covers 19.8% of the Poznań area. Surface water bodies constitute 3.7% of the city area. Almost 45.4% of the area within the city limits is built-up and contains transport infrastructure.

Poznań is located in a temperate climatic zone. In the 1848–2016 period, the average temperature in the city was 8.1°C (Kolendowicz et al., 2019); during this period, the average temperature increased
constantly, reaching 8.8°C in the years 1971–2015 (Bednorz & Tomczyk, 2020). The region of Poznań has one of the lowest rainfall rates in Poland. The average annual precipitation between 1971 and 2015 was 517.9 mm (Bednorz & Tomczyk, 2020). The considered and analysed present-day and expected climate changes show that in the coming years, the greatest threat to the urban economy and society will be extreme weather events resulting from climate change. These phenomena will occur with increasing frequency and intensity and will affect increasingly larger areas (Jania & Zwoliński, 2011).

3. Designing a geohazard map: materials and methods

3.1. Workflow

The creation of a thematic map poses several problems already at the presdesign stage. Fundamental issues
include the selection of the information to be included in the map and the sourcing of the required data. It is common to perform additional field research if no relevant geodata are available for the theme and/or (parts of) the area to be mapped. The next problem is the creation of an integrated and consistent geodatabase. The most crucial step is the creation of a catalogue of divisions to be included in the map. When determining these divisions, one should consider the questions of map scale, visualisation, and final appearance, and the effects of these on the legibility and perception of the map. The next issue is symbolisation: the selection of the size and colours of conventional signs, hatching, and font size and type. The final issues pertain to the composition (mock-up) of the thematic map: e.g. the consideration of legal requirements. The content, editing, and technical scope of a thematic map always present map makers with challenges.

### 3.2. Source data

The Poznań geohazard map was based on field mapping, digital and analogue data (Table 1), and archival materials.

To analyse the occurrence of extreme events in Poznań, the following materials were used:

- Catalogue of Local Flash Floods (Ostrowski et al., 2012)
- Catalogue of Torrential Precipitation (Lorenc et al., 2012)
- Climate adaptation plan for the City of Poznań until 2030 (44MPA, 2019)
- ‘SOPO’ Landslide Counteracting System of Poland (PIG-PIB, 2019a)
- Study of the conditions and directions of spatial development in the City of Poznań (PMP, 2014)
- Register of landslides and areas at risk of mass movement in the City of Poznań (Troć, 2010).

### 3.3. Data preparation

#### 3.3.1. Susceptibility to river flooding

The susceptibility to river flooding is a function of the elevation of a given cell above the nearest cell of the river bed with which it is connected by a runoff line (‘elevation above the channel level’ or ‘vertical distance to the channel bed’: a.c.l.). The elevation above the channel level was calculated using the r.stream.* package (Jasiewicz & Metz, 2011). This software uses multiple flow direction (MFD) to calculate all hydrological features, including vertical and horizontal distance to the channel. This technology is generally more suitable for lowland areas (Zhao et al., 2009). However, the condition of runoff connection limits the analysis only to the area before the watershed. It excludes areas beyond the watershed that may be connected to the Warta River through permeable deposits.

Hazard zones were established according to floodwater levels. Within the city limits, the Warta River is regulated along its course, so the extent of the waterbody on the map represents its full bank discharge. For geohazard assessment, the full bank discharge, representing the areas covered by water every year, is Level 0. Level 1 includes the areas between 0 and 2 m a.c.l., threatened by flooding every ten years (\( p = 10\%: \text{a high probability of flooding once every ten years} \)). This level is the ‘warning level’ for flood hazards. Level 2 is the ‘alarm level’ for flood hazards and comprises the areas between 2 and 2.9 m a.c.l. There, the risk of flooding is medium (\( p = 1\%: \text{a probability of flooding once every 100 years} \)). Level 3 comprises the areas between 2 and 4.9 m a.c.l. (the maximum recorded floodwater level). In this zone, the risk of flooding is very low (\( p = 0.2\%: \text{a probability of flooding once every 500 years} \)). A digital elevation model from the IT System for the Protection of the Country against Extraordinary Hazards (ISOK) programme was used to perform hydrological calculations. The model was cleaned, smoothed, and resampled at a resolution of 3 m to avoid the undesirable effect of small urban structures (of diameter below 3 m).

#### 3.3.2. Susceptibility to mass movement

The following criteria were used to determine the areas particularly at risk from gravitational mass movement: relative elevation, slope inclination, geology (lithological boundaries between sediments of different consolidation state and mechanical properties), hydrogeology (groundwater outflows, suffusion), and hydrology (river valley system, fluvial erosion). The slope length, or slope steepness factor (LS factor), is one of the factors of the Universal Soil Loss Equation (USLE). The LS factor was calculated using a standard formula in SAGA GIS software.

| Item                               | Resolution or scale | Source                                               |
|------------------------------------|---------------------|------------------------------------------------------|
| Digital elevation model (DEM)      | 1 m                 | State Geodetic and Cartographic Resource (GUGIK, 2019), adapted by Dąbrowski (2020) |
| Geomorphological Map of Poznań     | 1:100,000           | Hildebrandt-Radke, 2016                              |
| Detailed Geological Map of Poland  | 1:50,000            | Chmą (1996)                                          |
| Computer Map of Poland’s Hydrographic Division | 1:50,000 | KMPHP (2004)                                      |
| Hydrogeological Map of Poland      | 1:50,000            | Dąbrowski et al. (2000)                              |
Areas with LS-factor value above 100 were deemed to be at potential risk due to mass movement (Desmet & Govers, 1996).

3.3.3. Flash flood determination
The Topographic Wetness Index (TWI) expresses the tendency of a given area to acquire water. The index assumes steady-state conditions across the entire area and is independent of the infiltration and permeability of the area's sediment deposits. Although the index correlates well with soil moisture, it performs poorly on flat terrain (Western et al., 1999). The original SAGA Wetness Index was used but does not consider flow as an infinite thin film. Cells with low a.c.l. value result in a much more realistic TWI result than the standard approach (Böhner & Selige, 2006). Here, flash-flood hazard zones were established by thresholding the map at the level of 7.6, which best corresponds to the zones established by observation (Grzonka et al., 2008; PMP, 2015).

3.3.4. Susceptibility to wind erosion
In urban areas, susceptibility to wind erosion is limited to those parts where bare soil is directly exposed to wind activity. In Poznań, bare soils were identified directly from the 1-m-resolution Poznań City map (Dąbrowski, 2020) and the wind effect was calculated from the SAGA Wind Exposition Index. The latter is an averaged Wind Effect Index (Böhner & Antonić, 2009), calculated in all directions with angular step. The value of 1.02 was established as a suitable threshold for identifying all areas sufficiently elevated to be susceptible to wind erosion regardless of wind direction.

3.4. Map design
All information layers were compiled onto one sheet with the Poland CS92 coordinate system and the central meridian at 19°E (Main Map). The geomorphological map compiled by Hildebrandt-Radke (2016) and a Digital Elevation Model based on scanned 1:10,000 maps (GUGIK, 2019) were used as the background for the geohazard map. Before placing on the map, all geohazard layers were smoothed and generalised with mode (majority) filter, with the size of the processing window equalling 11 cells. This procedure also removed minimal areas below the level of map readability.

4. Results and discussion
4.1. Geohazard distribution
The geomorphological map covers approximately 30 types of landforms in Poznań, divided into four main morphogenetic groups (Hildebrandt-Radke, 2016; Zwoliński et al., 2017, 2018) (Table 2, Main Map). Two morphogenetic groups dominate the urban landscape, occupying over 62% of the city area: outwash plains and plains of various origin. Fluvial landforms, developed along the north–south course of the Warta River valley and its several latitudinal tributaries, occupy over 19% of the city area. Moraine hills and uplands are the least widespread landforms (<15% of the city area).

Mass movement and flash floods are the most significant geohazards, potentially affecting approximately 29% of the city area. Wind erosion has potentially impact on 3.1% of Poznań’s area. River floods can inundate 3.24–9.32 km², that is, only up to 3.7% of the city area. The following geohazards have the highest potential effect within each individual morphogenetic group:

- Within moraine hills and uplands: mass movement, wind erosion, and flash floods – a total of 12.4 km² (4.9%);
- Within outwash plains: mass movement and flash floods – a total of 21.8 km² (8.6%);
- Within fluvial landforms: mass movement and river floods in the maximum range – a total of 24.7 km² (9.8%);
- Within plains of various origin: flash floods, with an extent of 19.25 km² (7.6%).

This comparison shows that mass movement and flash floods, which can potentially affect 16 and 14% of the city area, respectively, are the most spatially widespread geohazards in Poznań. Mass movement geohazards concentrate on the short but numerous and locally steep slopes in the city (Figure 1B). Despite Poznań’s flat terrain, the risk of flash flooding is mainly concentrated in areas of extensive concrete and paving landcover.

4.2. Mass movement geohazards
In Poznań’s urban areas, a crucial triggers of mass movement in Poznań include meteorological conditions (high precipitation – further research is required for the determination of the rainfall threshold beyond which mass movements can begin), groundwater outflows erosion and suffusion processes, weakening of slope stability due to fluvial erosion and changes in pore-water pressure, and/or human activity (e.g. undercutting during construction works, additional burden of the slope, structural disturbance of the sediment, drainage blockage, vibrations from traffic, etc.).

The geological inventory carried out in Poznań registered several currently inactive landslides and identified areas at risk from mass movement (PIG-PIB, 2019b; Troć, 2010). The designated areas are
associated with the slopes of tunnel valleys and river valleys (around Lake Kierskie and the banks of the Cybina River), where there are significant elevation differences, high slope gradients (locally up to 16°), and substrate geological structures conducive to mass movement (Main Map). The highest risk of mass movement occurs along the Warta River valley. There, layers of Neogene clay at a depth of 6–10 m below ground dip towards the valley and are overlain by glacial tills, colluvial sands, and anthropogenic deposits. Groundwater outflows from the sandy layers, suffusion processes, and the presence of the Neogene clay layers, the upper part of which may constitute a slip surface, render these areas susceptible to shallow, transitional slides. In addition to the geological conditions, the loading of the slope by human-built structures contributes to the disturbance of the substrate (Figure 2A). Areas at risk of mass movement due to human activity were also identified. One such area is the A2 motorway in the southern part of Poznań. Landslides may occur on both sides of the road excavations, which were made in glacial till and covered with sandy embankments. Minor landslides were also observed along the Poznań Fast Tram route which follows a 6-m-deep excavation for a distance of 8 km. There, mass movement can be initiated from suffusion and animal burrowing (Figure 2B), e.g. by foxes (Vulpes vulpes; Mania, 2008).

4.3. Flash flood, urban flash flood and soil erosion geohazards (surface runoff)

The Catalogue of Local Flash Floods (Ostrowski et al., 2012) and the Catalogue of Torrential Precipitation (Lorenc et al., 2012) indicate that, in the years 1971–2015, there were 20 urban flash flood events in Poznań. The valleys of tributaries of the Warta River (mainly Bogdanka River, Cybina River, Główna River and Junikowski Stream) are most susceptible to flash flooding (Jawgiel, 2016). The areas of higher flood risk in Poznań are mainly excluded from urban development. Except for some areas with a few residential buildings, other flooding-prone areas were classified as green areas with special development conditions (e.g. allotments, parks, and other landscape green areas). In addition to the varied topography and the sealing of part of the catchment area, other causes of flooding include the small diameter of culverts, pipelines, and clean span, and the blocking of drainage facilities by debris. There are several areas in Poznań where the stormwater drainage infrastructure does not function effectively (Figure 3A). These areas are mainly located in endorheic basins and tunnels on the city’s left bank (Jawgiel, 2016). The online geoportal of the Poznań Flash Flood Project (2019) permits the ongoing analysis of inundation sites in the city.

Urban flash floods can inundate buildings in the urban environment, particularly in densely populated areas. They are triggered by torrential precipitation in areas of limited ground absorption capacity and insufficient or outdated drainage/stormwater infrastructure. Urban flash floods are associated with cascading urban geohazards, such as surface runoff and sheet wash. In various parts of the city, puddles and ponds may form in the streets and on sealed surfaces (Figure 3A), and rapid runoff may take place in areas of diversified relief. This increases the risk of flooding at places where runoff accumulates, and initiates water erosion on the slopes.

In the years 1961–2000, surface runoff made up approximately 10% of the water budget in Poznań’s urban catchments. In catchments with a high ratio of built-up areas (e.g. Bogdanka and Junikowski streams), this value reached 13–15% (Graf & Jawgiel, 2018). Analysis of the relationship between surface runoff and the soil of the drained surface (in undeveloped zones) showed that surface runoff is higher on poorly permeable clay soils (i.e. silty, silty-loam, and sandy-silty clays; Chmal, 1996). In Poznań, soil erosion may occur on biologically and hydrologically active surfaces with slope gradient over 2° – especially over 5° (Main Map). Such areas include the slopes of the Bogdanka and Junikowski streams valleys and the Warta River floodplain (Figure 1B), which can generate surface runoff (Graf, 2014). During precipitation and rapid snow melting, concentrated surface runoff on impermeable surfaces (such as pavements) adjacent to exposed loose soils can cause severe soil erosion.

4.4. Wind erosion geohazards

Wind erosion results from several co-occurring factors. Favourable conditions include a dry, sandy or
dusty substrate, no vegetation cover, and wind speed exceeding the threshold value for aeolian transport (usually above 3–10 m s\(^{-1}\); López, 1998). Due to the high roughness of the ground in the city, the wind loses its strength, and the threat of aeolian activity concerns scattered suburbs and arable land (Figure 1D). In Poznan, strong winds, of speeds above 10 m s\(^{-1}\), are recorded for approximately 40 days a year (Bednorz & Tomczyk, 2020), while very strong winds, of speeds exceeding 17 m s\(^{-1}\), occur for seven days a year on average (44MPA, 2019). Within Poznań’s city limits, the areas potentially susceptible to aeolian erosion cover 3.1% of the city’s area. On the agricultural land that lies within the city limits (SE, SW, NW, and NE parts of Poznań, Figure 1D: codes 2.1.1, 2.3.1, 2.4.2, 2.4.3), with loose podzolic and brown soils on sandy or clayey-sandy bedrock, aeolian processes intensify in the early spring (before vegetation growth), autumn (after the ploughing period), and winter (niveo-aeolian processes). Aeolian soil erosion is also triggered by large-scale urban construction works that involve the rapid removal of the vegetation cover and soil desiccation of large land surfaces. The neglect or overuse of public recreation and gathering places also makes their ground susceptible to wind erosion. Wind erosion geohazards intensified in the

Figure 2. Mass movement hazards in Poznań: A – The slopes of the Warta River valley in the inland port destroyed by a landslide (photo M. Makohonienko); B – foxes burrowing on the excavation slopes of the Poznań Fast Tram route (photo Zb. Zwoliński).
twenty-first century. Increasingly, deep cyclones of hurricane speed that may exceed 120 km h$^{-1}$, pass suddenly through Poznań throughout the year, damaging grey and green infrastructure by tearing off the roofs of buildings, breaking trees and branches and damaging energy lines.

4.5. Flood geohazards

The primary source of flood hazards in Poznań is the Warta River and its tributaries. The city has been subject to numerous floods in its history (Kaniecki, 2004). In the years 1501–1903, 69 floods occurred in Poznań (once every six years on average). After the great floods of 1888 (Figure 3B) and 1889, flood embankments were constructed in the downtown areas of Chwalszowo and Ostrów Tumski, on the left and right riverbanks, respectively. Further floods in the twentieth century CE necessitated the extension of the embankments. Poznań is protected from floodwater up to the level of about 58 m a.s.l. The last great flood in Poznań was in 1924 (Figure 3C). Since 1986, when the Jeziorsko artificial retention reservoir (42.3 km$^2$), in the middle of the Warta River course (about 260 km upstream from Poznań), became operational, the flood risk in Poznań has decreased. High floodwater levels in the city are associated with discharge above 400 m$^3$ s$^{-1}$ (WZKiB, 2015), and result in floodplain inundation. Recently, such high discharge events on the Warta River occurred in 2010 (Figure 3D) and 2011.

Studies and strategic documents (WZKiB, 2015) indicate that, due to the city’s geographical location and geomorphological setting, the operation of the Jeziorsko retention reservoir, and the presence of flood embankments and hydrotechnical devices (polders and bypass channels), Poznań is currently at moderate risk from river floods. The areas of higher flood risk are mainly those excluded from urban development (Main Map). The remaining areas exposed to flooding are classified as green areas with special development conditions (e.g. allotments, parks, and other landscaped green areas). With the current demographic condition of the city, a flood event with a probability of 0.2% would place 690 people at risk; an event with a probability of 1% would threaten 202 people; and one with a probability of 10% would threaten 131 people (PMP, 2015). Maintaining the current land use in areas particularly at risk of flooding, such as riverside boulevards, walking areas, and
recreational areas with bicycle paths, without introducing large buildings will ensure the safety of Poznań’s residents; at the same time, this will bring the river valley closer to the inhabitants of Poznań.

5. Conclusions

Geohazards triggered by climate change intensified at the turn of the twenty-first century. Our research provides new information on the spatial distribution of mass movement, flooding, and wind erosion geohazards in the city of Poznań, Poland (Main Map). This information can be useful, even for planners, to identify areas that require remedial operations and/or further, more detailed study.

In most parts of Poznań, the level of geohazard threat to the inhabitants is assessed as medium to low on a 4-point scale. Most of the city’s buildings are located outside the floodplain. This, together with the presence of flood embankments and a retention reservoir upstream of Poznań, protects most buildings from floods. Flooding occurs when the Warta River water level rises, but this mainly affects wastelands or green areas. Flooding due to torrential rainfall also occurs in agricultural areas or wastelands and does not directly threaten Poznań’s inhabitants. Inundation during urban flash floods occurs locally at faulty sewage receptors. The risk from gravitational mass movement is limited to the slopes of the Warta River valley or tunnel valleys occupied by the Warta’s tributaries and lakes. Small-scale mass movements have taken place along transportation lines that run in deep trenches and earth embankments (including a motorway and a speed tram line). During periods of drought, areas used for agriculture (however, gradually limited in the city landscape), are subjected to aeolian soil erosion before the growing season.

In recent years, the most significant damage in Poznań has been caused by high-speed cyclonic winds accompanied by torrential rain. On the one hand, Poznań suffers from a shortage of rainwater because it has one of the lowest values of annual rainfall in Poland. On the other hand, the asphalt, concrete, and pavement tile cover over a large part of the city’s ground forces much of the rainwater to run off quickly during each rainfall. In Poznań, the development of local retention basins, care for the valleys of small watercourses and water reservoirs, and the reduction of concrete and asphalt surfaces could have positive effects on the city’s water cycle. Poznań’s inhabitants should be considered comparatively safe from geohazards. This safety should be reinforced furtherly by adaptation measures to climate change, including maintenance and the development of integrated blue–green infrastructure.

This study did not consider extreme weather events such as heatwaves, extremely hot days, rainstorms, lightning/thunderstorm, droughts, severe winds, and fog, as we focused on selected geohazards only. Nevertheless, the intensification of these phenomena is posing an urgent research challenge.

Software

Saga GIS Software v. 7.0 (Saga Development Team, 2021); GRASS GIS (Grass Development Team, 2021) with r.stream extensions; QGIS 3.18.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [MM], upon reasonable request.

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