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INTRODUCTION

1.1. Research topic and objectives of the study

Analysis of the impact that non-typical events have on the performance of road transport systems in the literature shows that the field has yet to gain much attention from researchers in Poland, including those approaching the issue from the perspective of transport geography. While there are a limited number of studies on the impact of anthropogenic factors (including those related to the transport network itself) on the equilibrium of the transport system (considered mainly through the prism of traffic engineering), those devoted to the effects of natural factors on the performance of transport are rare. In order to fill this research gap, it is necessary to focus primarily on systematising the correlations between road transport and the non-typical phenomena that determine its efficiency (natural phenomena in particular) and to develop a methodology for analysing the strength and spatial range of this impact, and to draw synthetic conclusions on their role.

The review of Polish scientific literature on the subject matter discussed in this monograph clearly reveals a lack of comprehensive studies conducted with a spatial aspect in mind. One idea of the monograph was to conduct analyses both at different spatial scales (local, regional, and supra-regional) and within a scope to enable the eradication, or greatly reduce, the border effect. This ensures that regularities typical for transport systems at different scales are captured, and that observations of those phenomena which become visible only in a study that is spatially extensive enough to allow for their co-occurrence (e.g., their simultaneous occurrence in various areas within the transport system) become possible. The need for research into flood-related changes of transport accessibility and road network load in Poland is also justified by the significance of the issue on the international scale, where the number of publications, scientific conferences and periodicals devoted to the subject is continuing to grow rapidly. It seems well-grounded then that publications on the subject based on source data illustrating these phenomena in Poland should also appear within the national scientific corpus. The subject matter discussed in the monograph indicates its interdisciplinary nature, positioning the study at the crossroads of several research issues (including transport accessibility, spatial mobility, and crisis management). This is evidenced by the comprehensive overview it provides, the core elements of which can be found in the subsequent sections herein. On the national scale, the monograph can be positioned as an adjunct to the main research currents in transport geography, while on the international perspective, it seems closer to one of the important cognitive trends – having a character similar to numerous publications on related topics.

The importance of research into the effects that natural disasters have on road transport should be considered in the context of the increasing impact of weather and the greater reliance on the road network for people's lives. Even with no scientific evidence, and relying solely on media reports or personal observations, an increase in extreme weather phenomena is clearly noticeable, which, in ever increasing cases, may threaten the smooth functioning of road transport.

Floods are the most common natural disasters and generate widespread damage across the world (Jonkman 2005, Okazawa et al. 2011). Alas, researchers are convinced that the frequency of extreme floods will only increase due to climate change and land use (Posthumus et al. 2008 after Reynard et al. 2001, Brown and Damery 2002). The 21st century has seen an exceptional growth in car ownership in Poland, and considerable qualitative and quantitative developments in road infrastructure. Despite this investment in road infrastructure, it still falls short of that required, impacting the load on the road network. The authorities responsible are under constant and escalating pressure to meet the ever-growing demand. This pressure multiplies in the event of a non-typical event (e.g., a flood), when management of the transport system becomes a formidable challenge. Through effective decision making, the authorities are able to prevent transport exclusion and to counteract road network issues that directly impact both people's safety and the economy when faced with road closures, greatly reduced accessibility, and disruptive changes to the network load. What is more, human behaviour during the occurrence of non-typical phenomena, e.g., a flood that causes damage to a road section, is often unexpected and unlike that previously observed in studies, making further analysis thoroughly worthwhile (Pregnolato et al. 2017). This highlights the essential need for studies which could contribute to more effective responses to such situations in the future.

The importance of studies into changes in transport accessibility and road network load in the event of a flood should be seen through the prism of two spheres. Apart from its practical significance for the management of critical infrastructure (including transport infrastructure) when faced with an emergency situation and the mitigation of its negative effects on human life, health, and the economy (the primary goal of flood risk management), this research also has an important cognitive dimension. It allows one to assess the vulnerability of the Polish road network and the transport thereon to the destructive impact of floodwaters that may occur in regions of Poland in a scenario of a defined probability. Moreover, the research also enables the identification of areas particularly vulnerable to the negative effects of floods as regards the efficiency of the transport system. Thus, in addition to the spatial-environmental synthesis – which is considered a foundation of geographical research (Suliborski 2018) – the utilitarian nature of the monograph and its focus on the relationships between human activity and the forces of nature indicates that they are also contained within the material scope of spatial management (Domański 2002, Parysek 2006).

Research that combines analysis of flood-related issues, transport accessibility, and mobility is particularly important in view of flood-induced transport disruptions that may not only paralyse local transportation, but also have a knock-on effect on a nationwide scale, posing a direct threat to national security. It is important to be able to accurately estimate potential damage that may occur due to a flood. However, researchers too often focus on assessing direct material losses, while indirect ones are usually ignored, being difficult to express.

The monograph is an attempt to determine the impact that a non-typical event (here: a flood in a number of probability scenarios) has on transport accessibility and the road network load in specified water regions of Poland. The research was conducted mainly on the basis of secondary data on flood hazard areas in Poland and their management, including data on the road network and land use in their vicinity.

The purpose of the study is to assess the vulnerability of passenger road transport in Poland by identifying the nature and scale of changes in transport accessibility and the traffic load on the road network in the event of a flood.[1] This main purpose of the monograph has translated into a series of detailed objectives that are cognitive (1), methodological (2), and applicational (3) in nature.

(1) The cognitive objective includes identification of conditions (natural, environmental, legal and administrative, etc.) that determine the operation and development of road networks in flood hazard areas. The completion of this goal made it possible to develop a methodology for determining which segments of the road network become inaccessible during a flood (one of the methodological objectives), and to formulate recommendations for transport and spatial policies in flood hazard areas. The detailed (and key) cognitive objectives involved determining the nature and scale of flood-related changes in temporal accessibility at the municipality level (isochronous, cumulative, and potential), and identification of the nature of changes in traffic flow volumes (related to obligatory motivations) induced by closures of flooded road network sections and a reduction of traffic generators.

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[1] A fluvial or coastal flood of a high probability of occurrence (10%), of a medium probability of occurrence (1%), or in flood hazard areas due to a complete breach of stopbanks or the protective structure of the service strip in Poland.

(2) The first detailed methodological objective was to develop a procedure to identify those sections of the road network that are at a high and medium probability of flooding, or are affected when stopbanks or protective structures of the service strip are breached. The second objective was to construct a model of the road network presenting vehicle traffic speeds at a resolution that allows for intra-municipal analyses to be performed. Such a tool is indispensable for studying transport accessibility, since it renders the returned results more realistic. A high resolution is a prerequisite for the model to reflect – to an acceptable degree – localised flood-related changes within the transport system. The final methodological objective was to develop software (called RoadLoad) to enable the modelling of demand distribution across the transport system network, so that the returned results would allow the effective analysis and visualisation of the impact of the changes in the distribution of traffic that accompany non-typical events.

(3) This is also an applicational objective, since the software – with numerous features for modelling traffic distribution on the road network – can be used for the analyses of other criteria, e.g., studies that focus on other types of non-typical events. The detailed objectives are accomplished through the completion of the last (applicational) task; namely, formulating recommendations for spatial policy on the road transport system where it faces flood hazards. The conclusions drawn in the study will be translated into a number of proposals aimed at those decision-makers responsible for creating policies for flood risk management, and strategies for the development of transport infrastructure.

One accomplishment of the adopted research objectives is to validate the value of analysis of changes in transport accessibility, especially for flood hazard areas. The research results presented herein provide a basis to formulate and implement procedures that govern transport flows. This includes such traffic management measures as mandatory diversion signs displayed via VMS systems on motorways and expressways (for supra-regional travel) or changes in traffic organisation introduced by Intelligent Transport Systems (for intra-regional relations). Transport authorities can use the research results to develop strategies and operational plans, while the conclusions from this monograph may also become the basis for formulating guidelines for a programme to educate residents in flood hazard areas and their immediate vicinity, thereby shaping appropriate transport behaviour in emergency situations. At a regional or national level, this behaviour can be shaped by the said technical and technological solutions, while at a local scale, a key role is attributed to well-preparedness, since a flood may strike a community directly and suddenly. Not only would good practices in this regard mitigate the negative effects of flooding with regard to human health and life, but they would also increase the effectiveness of assistance provided by rescue services.

The monograph contains the results of the research project Changes in Theoretical Transport Accessibility and Load of the Road Network Resulting from a Flood on the Territory of Poland, implemented between 2019 and 2021 under the number 2018/29/B/HS4/01020, and funded by the National Science Centre in Poland.

1.2. Spatio-temporal scope of the study

The monograph presents analyses related to three research matters: land use and its development in flood hazard areas; transport accessibility; and spatial mobility (examined as one of its products, i.e., road traffic). Given the great complexity of the issue of transport itself and of the modes of transport available, there has been a number of attempts to systematically classify this phenomenon. This study was conducted with the assumption that trips are taken by car. The traditional division of transport applied by Polish experts in transport geography distinguishes two main classifications: vertical and horizontal. The former (also called modal) uses modes of transport as the main criterion to differentiate between transport subsystems. In this regard, the research presented herein relates to vehicular, land, and road transport (Koziarski 2007). The horizontal classification of transport is based on a number of criteria, including ownership, service frequency, objects transported (here: passengers) and scope (here: country) (Szymonik 2013).

Understanding the mutual relationships between the aforementioned research matters translates into comprehension of the impact that a flood has on transport accessibility in its temporal perspective, thereby enabling the identification of those sections of the road network that will be inundated. Travel isochrones between reference points (e.g., centroids of provincial capitals) are constructed for a road network under normal circumstances and for scenarios with flooded sections. The juxtaposition of isochrones for the periods when there is and there isn't a flood makes it possible to perform a quantifiable assessment of flood-related changes to travel times. Both population changes and spatial development within the range of the individual isochrones are indicators of possible accessibility issues. The analysis of spatial development involves, inter alia, gaining a better grasp of vehicle flows within the road network under normal conditions and in the event of a flood by applying different research scenarios. In order to visualise the vehicle traffic, it is necessary to use data on trip origins and destinations, and the volume of vehicles that move between them. The author analysed and visualised the trips for obligatory motivations that remain relatively steady (commuting to work and school, and business trips) even when there is a non-typical event. The volumes of vehicle flows were scrutinised for a "normal" road network load, and for flood-related changes to the load on individual sections of the road network considering the structure of the load by road category.

The effects of floods are a subject of interdisciplinary studies, which take into account a variety of aspects including natural, economic or social factors (Kowalczak 2008, Piepiora and Brzywcz 2017). Particularly relevant for the subject matter of the monograph are economic aspects, e.g., damage to transport infrastructure. These include costs incurred to restore a damaged road network to its pre-disaster state and to protect it against any future floods (Kryk 2003). While the presented study does not refer directly to losses in the social sphere, these should also be mentioned. For instance, the necessity for organised or self-evacuation from areas at risk may be seen as affecting the quality of life. As for the spatial consequences, they are often manifested by changes in land use within flood hazard areas, or by shifts in spatial policies (Piepiora 2019), of which the transport component is an integral part.

The scope of the research presented in the monograph reflects the two major purposes of flood risk management – reducing risk and improving risk management, especially reducing the vulnerability of infrastructure (here: transport) and communities (here: road users) to flood; increasing the resilience when rebuilding the road network; restoring the transport system to its pre-flood state; and developing educational programmes to improve the awareness and knowledge on how to cope with flood risk and hazards (e.g., during self-evacuation from flood hazard areas).

Provisions in the existing flood risk management plans for each river basin indicate the need to restrict or prevent any more land use within areas at high risk of flooding (fluvial or coastal) by prohibiting the erection of new infrastructure and facilities or by changing the use of existing ones.

Managing a transport system in a flood hazard area can be examined for two time perspectives, since the period after the flood can also be considered a period of "waiting" for its recurrence. Thus, for road network operators, the period of "normal" conditions is time that should be spent on preparation, prevention and restoration. During floods, however, it is necessary to react immediately, e.g., to close bridges and roads to traffic or to decide on diversions. It should be emphasised that activities to directly protect (critical) road infrastructure during a flood cease to represent flood management *per se* and transform into emergency management (Fox 2003, Piepiora 2019).

The temporal scope of the study was mainly determined by the availability of the key source databases used in the monograph. This refers primarily to data from the IT Country Protection System, in particular that which was developed under the responsibility of the Head Office of Land Surveying and Cartography in Poland. Acquisition of elevation data by airborne laser scanning technology and the subsequent development of the Digital Terrain Model (DTM) and the Digital Surface Model (DSM) on its basis took place between the fourth quarter of 2010 and the first quarter of 2015. The elements of the Database of Topographic Objects, on the other hand, were prepared between the fourth quarters of 2011 and 2013. The flood hazard and risk maps whose vector databases were an important constituent of the research procedure were prepared between 2008 and 2013, while the flood risk management plans were not finished until two years later. The large timespans that surfaced when the data was being prepared stem from the complexity of the methodology applied to process it, and the vastness of the territory for which it was collected and processed. This created a problem of up-to-datedness of the source data, which posed a significant methodological challenge. It was necessary to devise a way (described in detail in Chapter 4 herein) to eliminate the time gap between the year of source data validity and the period for which the models of the national road network and of car traffic speeds were constructed. In this respect the study used the data on road investments at the level of municipality, district, province and country, covering the construction projects in the years 2011–2019. The road network and speed models reflect the situation for the third quarter of 2019 – a period that should be considered the main timeframe of the study. This period was also applied when laws on the issue in question were reviewed and analysed. Certain statistics within the generator-attractor data on motivations behind commuting (to school) and business trips come from 2018. In the case of matrix data on commuting to work, its availability also required the application of a certain time shift, since the latest data on the subject covers the year 2016.

The spatial scope of the study is strictly limited to the road network, with the model encompassing the whole territory of Poland and a buffer area of several dozen kilometres around the country's borders. The network includes all motorways and expressways, national, regional, district roads, as well as a substantial portion of local roads. The applied buffer zone was to make the results of the simulation more realistic, and to enable the inclusion of vehicles avoiding closed road sections (due to flooding), and instead availing of the road infrastructure located outside the territory of Poland (administrative borders not constituting a barrier when a route is selected). The buffer was defined so that in no scenario would the "artificial" border of the analysis affect the results. For the state borders with Belarus, Ukraine, and Russia, a methodology reflecting the restrictions from border checks was applied.

The analyses were conducted for three flooding scenarios: areas of a high (10%) and medium (1%) probability of flooding (including coastal floods: 1%C), and hazard areas at risk of flooding due to a complete breach of a stopbank (SB) and the protective structure of the service strip (SSB). Flood simulations were performed for all thirteen water regions of Poland – in the river basins of the Vistula, the Oder, and the Pregolya – and for the three largest rivers – the Vistula, the Oder, and the Warta. Naturally, any attempt to classify or categorise such a complex phenomenon as a flood is problematic, forcing the researcher to apply some form of delimitation when considering the spatial changeability of the disaster. As a result, the author decided to use water regions (not administrative units), since they are delineated on the basis of a hydrographic criterion, and thus, they seem to better reflect the purpose of the study. In addition, their number and spatial distribution allow simulations to specifically capture the variety of impacts that floods have on the road transport system in Poland. Based on this rationale, the flood simulation analyses of changes in transport accessibility were conducted at a regional and local level, whereas analyses of changes in the road network load were performed at an inter-municipal scale.

1.3. Data sources

In order to accomplish the research objectives adopted in the monograph, the author used six major types of source material:

- data that includes the content of digital flood hazard and risk maps (the product of the IT Country Protection System);
- data used to build the models of the road network and the speed of passenger vehicle traffic;
- data on types of land use other than road infrastructure;
- data on the distribution of the population;
- data on infrastructural investments in the road network;
- statistical data necessary to determine traffic-generating potentials, a matrix of residents' work-related mobility, and potential accessibility.

The first type primarily included the selected reference layers. Flood hazard maps were used to determine areas at risk of fluvial and coastal flooding within individual water regions, as well as water levels and maximum ordinates of the water table. Flood risk maps were applied to determine land use and possible damage to property, as well as the layer showing structures (which contains information on the number of residents in each building). This data was obtained from the resources of the State Water Holding Polish Waters, and it also included a digital surface model used to identify sections of the road network that would be shut down during a flood. The model was made available by the Head Office of Land Surveying and Cartography in the ASCII XYZ GRID format.

The model of the road network was built mainly on the basis of the Database of Topographic Objects (by the Head Office of Land Surveying and Cartography), vector data from OpenStreetMap resources, and selected data from road infrastructure authorities. In order to develop the speed model for car traffic it was also necessary to prepare secondary vector data on the location of junctions within the analysed road network, and to include a data layer on buildings (from the Database of Topographic Objects) and populations. These were obtained from a commercial provider and compiled on the basis of information acquired from the resources of the Ministry of the Interior and Administration, the Central Statistical Office, and municipal offices. The data on population distribution (aggregated to the level of street/road) was further supplemented by a database containing information on settlement units in Poland, including the number of residents in each unit.

In addition to the data illustrating the structure and other selected properties of the road infrastructure, the study took into account extensive spatial information including, inter alia, administrative borders (the Head Office of Land Surveying and Cartography), the location of fire brigades, and sites of nature conservation (the General Directorate for Environmental Protection).

Data on investments in road infrastructure was retrieved from the General Directorate for National Roads and Motorways, more precisely from the Programme for the Construction of National Roads for the Years 2014–2023 (with proposals up to 2025), which the General Directorate for National Roads and Motorways is currently following while implementing investments in national roads, and from investment projects for the existing road network that are related to the expansion and upgrades[2] of road sections, the improvement of road traffic conditions, safety, as well as traffic management systems. Information collected by the road authorities of individual regions was also used, regarding investments implemented, inter alia, within the framework of the Integrated Regional Operational Programme, the Province Regional Operational Programme, the Operational Programme for Development of Eastern Poland, subvention funds for co-financing investments on local roads, funds from the Ministry of Infrastructure and Development, subvention funds of the Ministry of Infrastructure and Construction, and funds provided by individual provinces. Regional governments provided data on investments implemented under the National Programme for Redevelopment of Local Roads (2008–2011, Stage II – Safety, Accessibility, Development), the Government Programme for the Development and Competitiveness of Regions through Improvement of Local Road Infrastructure, the Programme for Development of Municipal and District Road Infrastructure in 2016–2019, the European Union Solidarity Fund (emergency measures taken to overcome the effects of floods in May and June 2010, initiated in order to restore municipal infrastructure to its pre-flood

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[2] Execution of roadworks resulting in an upgrade of the technical and operational parameters of an existing road that do not require a change in the boundaries of the existing footprint of the road (Act of 21 March 1985 on Public Roads, Journal of Laws 1985, No. 14, Item 60, as amended).

state as quickly as possible), and funds from the state budget allocated to alleviate the effects of landslides or other effects of natural disasters. Whenever it was necessary to verify whether a given section of a district or local road was built, or if its important parameters had changed after the data for the production of the DTM and DSM models had already been acquired, and the section was not listed in the aforementioned datasets, the appropriate authority or municipality office was contacted.

1.4. Glossary of key terms

As the monograph employs terminology from a number of disciplines outside transport geography (including traffic modelling and simulation, spatial information systems, flood risk management, emergency management and critical infrastructure protection), the author decided to include a glossary of terms used in the study to facilitate its reception. These terms broaden the semantic meaning attributed to them in this sub-discipline of geography, as already seen in the literature (e.g., Rosik et al. 2018). There is also a set of terms within the field of transport geography itself for the research topic addressed which do not commonly appear in the Polish literature on the subject. The definitions have been listed alphabetically within each thematic area, taking into account the specificity of the study in question.

As regards transport geography:

• **adaptability** of the transport system – the ability to adapt to post-event circumstances until a state of transport equilibrium is reached (Faturechi and Miller-Hooks 2014a). Adaptability is defined as one of the resilience features of a system, reflecting its ability to respond to the occurrence of destabilising factors. The key element here is the dynamics of the response assessed against the complexity of the system under study (Fiksel 2003, Dalziell and McManus 2004, Bhamra et al. 2011, Wan et al. 2018);

• **exposure** of the transport system to the occurrence of a non-typical event – the consequences of a dangerous event determined precisely for a given place in the system (Jenelius and Mattsson 2006);

• **flexibility** of the transport system – the ability to react to the occurrence of a non-typical event and to adapt to the changes that have happened through the implementation of contingency measures taken after the disruption has occurred. It should not be confused with robustness, which is the ability of a network to remain unchanged despite the occurrence of an incident, rather than adapting to it (Goetz and Szyliowicz 1997, Cox et al. 2011, Berle et al. 2013, Faturechi and Miller-Hooks 2014a, Wan et al. 2018);

• **importance** of the component of the transport system – the aggregate effect of the occurrence of a dangerous event in a given place on the whole system under study (Nicholson and Du 1994);

• **redundancy** of the transport system – the ability of certain parts of the network to perform the tasks normally conducted by parts that are currently adversely affected by non-typical events, without compromising the performance of the whole system. Redundancy is most commonly associated with the existence of alternative routes, e.g., to be taken instead of a road currently inundated by floodwaters (Fiksel 2003, Haimes 2009, Omer et al. 2012, Tukamuhabwa et al. 2015, Wan et al. 2018);

• **reliability** of the transport system – the probability that the road network will be operational when a non-typical event occurs (Barker et al. 2013, Faturechi and Miller-Hooks 2014a). As regards road journeys, it is the degree of confidence with which a road-user is able to estimate how long a trip will take. This confidence depends on probability distribution and on the stability of travel times; the available information on the condition of the transport system, and the travel options at hand (Immers et al. 2004, Jenelius et al. 2006, Jenelius and Mattsson 2012);

• **resilience** of the transport system – the ability of a transport system to maintain the "normal" level of service (Holling 1973, Scheffer et al. 2001) or to restore the level of service preceding a flood over a specified period of time (Holling 1973, Bergen et al. 2001, Bruneau et al. 2003, Leveson et al. 2006, Murray-Tuite 2006, De-Los-Santos et al. 2012, Miller-Hooks et al. 2012, Do and Jung 2018, Wan et al. 2018). It encompasses pre-event mitigation and ongoing preparedness for hazardous events (Vugrin et al. 2010, Chen and Miller-Hooks 2012, Miller-Hooks et al. 2012, Zhang et al. 2015). The concept of resilience is applied when the occurrence of a disturbance is examined from a dynamic (timeline) perspective. Due to the broad semantic scope of this concept, it "accommodates" a considerable part of the terminology referred to in this thematic field;

• **resourcefulness** of the transport system – the preparedness of the transport network to return to a state of minimum acceptable operational efficiency. Resourcefulness is defined as the availability of resources to restore network operability. It is one of the elements of a road network's resilience (Adams et al. 2012, Reggiani 2013, Francis and Bekera 2014, Wan et al. 2018);

• **robustness** of the transport system – the ability of a network to continue operating in non-typical circumstances (Knoop et al. 2012); the ability to withstand or absorb disturbances and maintain operability in the face of a disturbance (Blockley et al. 2012, Faturechi and Miller-Hooks 2014b, Wan et al. 2018);

• **survivability** of the transport system – the ability of elements of the road network to withstand the sudden onset of the initial effects of a non-typical event (Adams et al. 2012, Reggiani 2013, Baroud et al. 2014, Faturechi and Miller-Hooks 2014b, Francis and Bekera 2014, Wan et al. 2018);

• **susceptibility** of the transport system – the ease with which elements of a transport network are affected by an event (e.g., a flood) that weakens one or more connections within its range, considered in terms of the ability of the network to maintain a baseline level of performance (Jenelius et al. 2006, Jenelius and Mattsson 2012, Oliveira et al. 2014);

• **vulnerability** of the transport network – the susceptibility of land use and development (e.g., transport infrastructure) to hazard/damage and the ability to counteract and recover, e.g., from flooding (Berdica 2002, Merz and Thieken 2004, Jenelius and Mattsson 2006, Chen et al. 2007). A distinction is made between connective vulnerability and access vulnerability (Chen et al. 2007). Vulnerability is thus composed of physical, social, economic and environmental factors or processes that increase the sensitivity of a transport network to flooding. Vulnerability is a property of a given transport system that can weaken or limit its ability to cope with a hazard (destructive events that have occurred inside and/or outside the system) (Asbjørnslett and Rausand 1999, Blockley et al. 2012, Wan et al. 2018).

As regards traffic modelling and simulation:

• **capacity** – maximum possible density of vehicular traffic on a given internodular section of the transport network (Krych 2018, s. 77);

• **congested transport network** – a condition of a given transport network when the average transport performance depends on traffic flow density within the network elements and the degree of inconvenience that forces users to change their transport decisions. Congestion involves the presence of critical points on the network where demand exceeds their capacity within the time interval specified. As demand grows, the length of the time interval increases, thereby expanding the congested area to neighbouring sections of the network (Krych 2018, p. 100).

• **deferred traffic** – part of traffic flows captured within a given transport network by alternative transport routes due to change in: transport costs on sections of the network induced by changes in the shape of the network (e.g., shutting down a flooded segment of the road network), traffic organisation (e.g., diversions imposed to circumnavigate flooded areas), or the capacity of network components (e.g., closing lanes damaged by floodwaters) (Krych 2018, p. 81);

• **free-flow traffic** – a condition when the density of vehicular traffic has no impact on transport costs for co-users in a given traffic flow (Krych 2018, p. 84);

• **induced or suppressed traffic** – part of traffic flows impacted by a change (increase or decrease) in traffic generation and attraction due to changes in transport costs within the structure of transport supply (Krych 2018, p. 82);

- **intercepted traffic** – part of traffic flows captured by an alternative transport network due to a shift in the transport cost ratio between the modes of transport pertinent to these networks (Krych 2018, p. 82);
- **road conditions** – geometrical attributes that characterise the spatial location (horizontally and vertically) of the road axis, as well as the shape, properties and physical conditions of its cross-section (Wiedemann 2019);
- **traffic conditions** – the sum of factors affecting (temporarily and locally) drivers on the road, determining the flow of traffic, e.g., percentage of vehicle classes, weather, visibility, etc. (Wiedemann 2019);
- **traffic flow model** – also known as "transport demand model" or a representation of the structure of transport demand; it presents the transport decisions made by users as mathematical functions that depend on the supply structure of transport and the structure of spatial development in the time interval allocated to the model within a given territorial unit. Traffic flow models are employed to forecast traffic in studies into changes in traffic flows when planning transport systems, optimising transport networks, solving transport issues, and supporting decisions regarding other transport-related problems in transport networks (e.g., the occurrence of non-typical events) or transport systems (Krych 2018, p. 50);
- **traffic forecasting** – analysing the response of transport demand to changes (e.g., caused by non-typical events) within the transport system (e.g., section closures), transport behaviour (e.g., self-evacuation), and land use by utilising a traffic flow model with incorporated transport interaction and transport network models while taking into account changes in traffic generators. The product is a traffic forecast for a territorial unit within a specified time horizon (Krych 2018, p. 74);
- **traffic generation** – the ability of certain land-use and development components to generate traffic, expressed as a ratio between the number of trips started in a certain time unit and the size of a given land-use and development component (Krych 2018, p. 82);
- **traffic structure** – representation of the spatial distribution of traffic over a certain period of time graphically or, for operational purposes, as a mathematical square matrix with dimensions corresponding to the number of transport regions within and outside the delimited territorial unit. Sometimes called an O-D (origin-destination) matrix, it is applied for operational activities in traffic flow modelling (Krych 2018, p. 94);
- **traffic volume counts** – the number of vehicles (in traffic flows per unit of time) or transport performance (tonne-kilometres, passenger-kilometres, vehicle-kilometres, etc.) allocated to a specific set of nodes within the transport network or transport regions. Being a property of transport demand, traffic volume counts are a reference to the properties of transport supply: maximum

traffic density as the capacity of a given section of the transport network versus maximum transport performance as the capacity of the transport network or its designated section (Krych 2018, p. 49);

As regards spatial information systems (Wężyk 2015):

- **airborne laser scanning (ALS)** – a method of acquiring information on terrain and land cover. The concept of airborne laser scanning equates to the laser measurement of the distance between a flying aeroplane, helicopter or any other aircraft, and the surface of the ground;
- **Digital Surface Model (DSM)** – digital representation of the terrain relief and the objects there (buildings, vegetation, etc.);
- **Digital Terrain Model (DTM)** or **Digital Elevation Model (DEM)** – a set of points representing the topographic elevation of the terrain surface together with an interpolation algorithm allowing the reconstruction of that surface at any location;
- **LiDAR** – an acronym for "light detection and ranging," synonymous with laser scanning, where a laser scanner is a system consisting of a coherent light emitter and a reflected light receiver to determine the distance to an object;
- **LiDAR data** – elevation data acquired using airborne laser scanning; synonyms: ALS data, ALS measurement data, ALS point cloud, LiDAR point cloud;
- **LiDAR products** – measurement data from airborne laser scanning, the Digital Surface Model (DSM) and the Digital Terrain Model (DTM) derived from it, and aerial photographs produced as part of the IT Country Protection System.

As regards flood risk management:

- **area at elevated risk of flooding** – areas where there is a medium probability of flooding (1%); areas where there is a high probability of flooding (10%); areas between shoreline and a dyke or a natural high shore incorporating a dyke, as well as islands and alluvial banks which are registered as separate parcels of land (referred to in Article 224) containing the service strip (Act of 20 July 2017 on Water Law, Journal of Laws 2017, Item 1566, Article 16, p. 34);
- **area at risk of flooding** – an area where a significant flood risk exists or is likely to occur (Act of 20 July 2017 on Water Law, Journal of Laws 2017, Item 1566, Article 16, p. 33);
- **area potentially at risk of flooding** – an area identified on the basis of flood protection studies, historical data, geomorphological analyses, studies on the impact of water control facilities on flood safety, long-term forecasts of trends (including the impact of climate change on the frequency of floods). This type of area is taken into consideration when determining areas at risk of flooding (Updated Methodology for Preliminary Flood Risk Assessment, p. 11);

• **coastal strip** (understood as “coastline”) – the land adjacent to the seashore and consisting of: the service strip – a zone of direct mutual interaction between the sea and the land (designed to maintain the shore in a condition compliant with the requirements of safety and environmental protection), and the protective strip which covers the area where human activity has a direct impact on the condition of the service strip (Act of 21 March 1991 on Maritime Territories of the Republic of Poland and Maritime Administration, Journal of Laws 1991, No. 32, Item 131, Article 36);

• **flood** – an overflow of water that temporarily submerges land that is usually not inundated, in particular caused by water surges in natural watercourses, reservoirs, canals and from the sea, with the exception of overflows caused by water surges in sewer systems (Act of 20 July 2017 on Water Law, Journal of Laws 2017, Item 1566, Article 16, p. 43);

• **flood risk** – the combination of the flood probability and the possible negative effects of flooding on human life and health, the environment, cultural heritage and businesses (Act of 20 July 2017 on Water Law, Journal of Laws 2017, Item 1566, Article 16, p. 48).

• **river basin** – an area of land and sea, consisting of one or more adjacent catchment areas together with all the connected groundwaters, internal marine waters, transitional waters and coastal waters (Act of 20 July 2017 on Water Law, Journal of Laws 2017, Item 1566, Article 16, p. 31);

• **water region** – part of a river basin identified on the basis of hydrographic criteria for the purpose of managing water resources, or part of an international river basin located within the territory of the Republic of Poland (Act of 20 July 2017 on Water Law, Journal of Laws 2017, Item 1566, Article 16, p. 46);

As regards emergency management (Act of 26 April 2007 on Emergency Management, Journal of Laws 2007, No. 89, Item 590):

• **critical infrastructure** – all the systems and their functionally interconnected facilities (including buildings, equipment, installations, services) that are critical to national security, citizens’ safety, and the smooth operation of public administration institutions and businesses (Article 3, p. 2);

• **critical infrastructure protection** – all measures taken to secure the operation, continuity, and integrity of critical infrastructure in order to prevent hazards, threats, risks or vulnerable points, and any actions implemented to mitigate and neutralise their effects, leading to the timely restoration of that infrastructure in the event of failures, attacks or other disruptive events (Article 3, p. 3);

• **emergency (situation)** – a situation which adversely affects the safety of people, causes widespread damage to property and/or the environment, and imposes significant constraints on the performance of public administration bodies due to insufficient capacities and resources on their side (Article 3, p. 1).

1.5. Structure of the monograph and schedule of the research procedure

The structure of the monograph stems from the nature of the main and detailed research objectives. It consists of nine chapters, including an introductory part and a conclusion. The introduction to the research issue and the objectives of the study, including its thematic focus, and the definition of the temporal and spatial spectrum, the range of source materials and the conceptual outline of the work are followed by the implementation of subsequent research assumptions.

In structuring the monograph, the author sought to maintain a layout with the level of universality as shown in the following diagram (Figure 1.1):

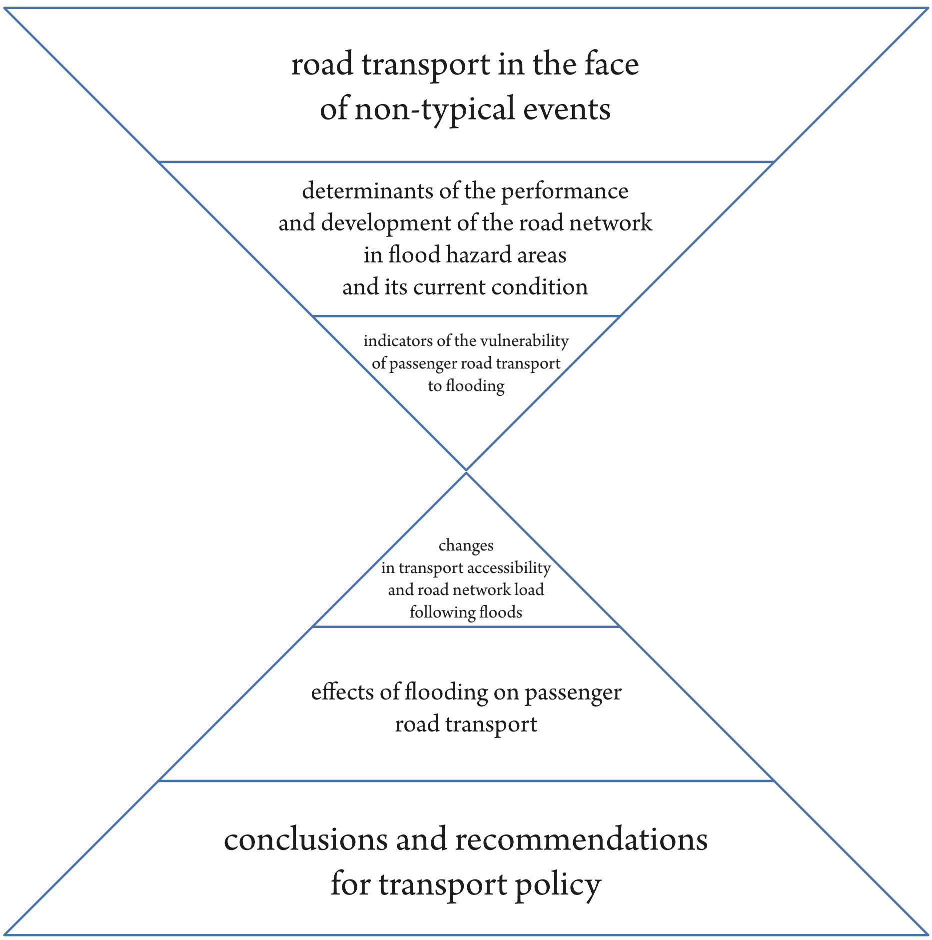

Figure 1.1. The layout of the monograph
Source: own elaboration

The research procedure begins with "general" reflections on the impact that various non-typical events have on road transport, before shifting the focus specifically to flooding. This is followed by a discussion on the methodology of investigating the correlations between accessibility and the road network load. The presented methods are a tool to execute the major empirical part of the study. On the basis of detailed findings, a synthesis of the results and their possible utilisation is conducted, taking into account the factor of spatial cohesion and changes to the transport system resulting from the implementation of investments in infrastructure. The research procedure ends with conclusions and recommendations for the transport policy, both specifically related to the conducted simulations and universal ones. The review of the literature does not adopt the traditionally concise format but is presented in steps, throughout several sections of the monograph where considerations on the subject matter of the review are undertaken.

The research procedure formulated in this manner determines the structure and content of individual parts of the monograph. In Chapter 2, the operation of the road transport network in the event of non-typical occurrences is addressed, providing an introductory outline of issues with regard to their impact on the capabilities and performance of the transport system. This part discusses various types of non-typical events and their different effects on transport. Against this background, the phenomenon of flooding and its impact as a hindrance to transport is scrutinised. Types and properties of floods are presented, followed by a synthetic description of historical flooding events with particular focus on transport, and, most importantly, a detailed analysis of studies into the impact of floods on road transport is conducted, including those related to the process of evacuation.

Chapter 3 discusses the operations and structural development of the road network in flood hazard areas. The key attributes of the natural environment and the floods that may occur are specified for each water region, taking into account the underlying conditions for each. Another sub-chapter focuses on both the population and land use within flood hazard areas. It provides information on the types of land use therein, with particular focus on those related to transport infrastructure and the magnitude of potential flood-related losses. The distribution of the population in areas at risk of flooding is analysed, including any significance with regard to evacuation and the impact on traffic conditions. Legal and administrative issues regarding both general land use in areas at risk and specific issues directly related to road infrastructure are also examined.

Chapter 4 presents a discussion on the impact of floods on infrastructure. This section describes segments of the road network at risk and the methodology for identifying sections inundated by floodwaters (including verification of the necessity to close bridges). The issues addressed therein include hydrodynamic modelling, the use of LiDAR products, and databases of investments in infrastructure executed by individual road network operators.

Chapter 5 focuses on flood vulnerability indices for passenger road transport. Firstly, the concept of transport accessibility is defined and the methods for its analysis are reviewed with emphasis on the assumptions made in this particular research procedure. The assumptions of a speed model for car traffic are also presented there. The second part of the chapter provides an introduction to the issues of mobility, road network load, and methods applied to measure, simulate and model traffic. Chapter 5 concludes with a description of the functionality behind the tool for modelling traffic distribution on the road network.

The empirical Chapters 6 and 7 present the results from applying the previously presented methodology to determine both transport accessibility and road network load. The penultimate section of the monograph (Chapter 8) offers a synthesis of the returned results and introduces forecasts that take into account the planned development of the road infrastructure. The monograph ends with empirical and methodological conclusions, including recommendations for transport policy with a view to reducing the vulnerability of the road transport system to floods (Chapter 9).

2

NON-TYPICAL EVENTS IN ROAD TRANSPORT

2.1. Review of non-typical events

Transport is defined as a stage of the production process that involves the movement of people (passengers) and cargo from one place to another (Berezowski 1975, Dziadek 1986). In its broader perspective, it can be described as any activity that traverses distance using a technological means to cover that distance (Tarski 1973, Lijewski 1986). Thus, transport is easily distinguished from other stages of the production processes by its technical, organisational, and economic aspects to purposefully move cargo and passengers (Mindur 2005). The topic of transport is inextricably linked to geography, due to, in particular, the nature of space and the space-related phenomenon of distance decay. Rucińska (1998) notes that the intentionality of movement results directly from the spatial incompatibility between the elements necessary for human activity. This incompatibility delineates the locations of trip origins and destinations, while distance decay, combined with the human drive for optimisation (the pursuit of the lowest costs possible), shapes the travel matrices and the spatial distribution of traffic. Organicism-based theories compare transport to the circulatory system in a living organism, here – a socio-economic landscape (Gołembska and Szymczak 2004) that seeks homeostasis (Parysek and Mierzejewska 2013), which makes it vital to identify sudden disturbances within the transport system, including its road component as it enables effective risk management.

Despite the great relevance of the topic of transport, those researchers who undertake to explore it face obstacles, namely the insufficient empirical data and the dearth of decision-support tools. A considerable number of studies into the susceptibility of road networks adopt, primarily, a qualitative approach, mainly due to the scarcity of accurate quantitative data on the subject (Chen et al. 2007). There is also a wide discussion in the literature on defining the concept of road transport vulnerability (Einarsson and Rausand 1998, Berdica 2002, Jenelius et al. 2006, etc.). Berdica (2002) characterises the phenomenon as susceptibility to events that may severely reduce the operability of the road network (Berdica 2002, p. 119, Holmgren 2004, p. 12), a concept that has gained relatively high acceptance in scientific circles (Yang et al. 2013). D'Este and Taylor (2003) deem a network component susceptible if the loss of a small number of connections dramatically reduces its accessibility (or significantly reduces its performance). The importance of a given component (a section, a node, or a group of sections and/or nodes) within the network encompasses both the probability of failure for that component and the impact of its failure on the whole system. The more important a given component is, the graver its failure is for the entire system. If the probability of such a failure is high, this component (e.g., a section of the network) is considered at risk. And if the consequences are significant, the component is considered important. A component can be considered critical when it is both at risk and important (Nicholson and Du 1994, Borowska-Stefańska et al. 2018).

Changes in performance within the network usually impact a significantly larger area than just that directly affected and can last considerably longer than the duration of the incident itself (Jenelius and Mattsson 2012, Borowska-Stefańska et al. 2018, Do and Jung 2018, Borowska-Stefańska et al. 2019a). Disruptions to the transport network cover a wide range of scenarios, regarding both the probability of occurrence and the negative effects. These range from the occasional minor accident to much less likely situations, e.g., serious damage to bridges (Berdica 2002).

Disruptions to the road network then can be divided into typical and non-typical (Chen et al. 2016). The former occur due to the imbalance of transport demand in time and space and are recurrent within a certain amount of time. A direct effect of disruptions caused by an excessive transport demand that appears at the peaks of individual time cycles combined with a limited road capacity is recurring congestion (Grant-Muller and Laird 2007, Żochowska and Karoń 2012). Others include – underdeveloped or ill-designed transport infrastructure; flaws in traffic organisation (e.g., poorly calibrated traffic lights); the presence of level crossings. Recurring congestion is particularly burdensome at rush hours, which (especially in urban areas) may cover a significant part of the day (Karoń and Mikulski 2011, Żochowska and Karoń 2012, Borowska-Stefańska et al. 2018). Recurring congestion may also exhibit a high degree of randomness, especially as regards the duration and effects of traffic disruptions. Above all, typical disruptions affect the key components of the transport network when limited capacity renders them unable to meet transport needs, meaning they are highly susceptible to disruption, thereby turning them into bottlenecks for the whole system (Dybicz 2014).

Besides these typical disruptions caused by insufficient network capacity, there are also non-typical disruptions which stem from abnormal temporary conditions or circumstances brought about by unfortuitous events (roadworks on the carriageway or in its immediate vicinity, mass gatherings that require temporary changes in traffic organisation, etc). Other causes include traffic incidents, unfavourable weather conditions, a sudden worsening of road surface quality, or even terrorist attacks. Non-typical disruptions lead to non-recurring congestion (Skabardonis et al. 2003, Grant-Muller and Laird 2006, Jacyna 2009, Chung 2012, Żochowska and Karoń 2012), whose probability and magnitude varies depending on the type of network, and its redundancy and susceptibility to disruptions. These disruptions are partly determined by how effective local risk management is, but also by roadwork scheduling and the measures taken to remove those obstacles impeding a smooth and free flow of traffic. Although most non-typical disruptions bring negative effects for road traffic, not all exhibit the same degree of unpredictability. Even adverse weather conditions can be handled more effectively through active traffic management systems and the preparation of contingency plans which can significantly reduce the negative impact on traffic (Żochowska and Karoń 2012).

Non-typical events that damage the road network or cause failures in road infrastructure and its components may result in a partial or complete closure of a given network section. Marcinkowski (2006) shows that these failures may be not only due to factors directly related to road use but also include unrelated factors (even the product of deliberate actions). These unrelated factors include weather and geological conditions as well as human behaviour that is not directly related to the use of the road network (protests, demonstrations, riots, etc.).

When assessing the vulnerability of the road network to non-typical events, the researcher must take into account the functionality (importance), technical specifications and spatial course of its individual sections. The assessment criteria are very specific for intentional damage, e.g., deliberate destruction of infrastructure during a war. However, such incidents are not discussed in detail herein, as they are extremely rare in Poland's geopolitical situation of Poland and their nature and genesis differ substantially from all other peacetime non-typical occurrences.

Climate and weather conditions significantly determine how road infrastructure is incorporated into the geographical space and its subsequent operation (Brijs et al. 2008, Antoniou et al. 2013, Mitsakis et al. 2014). In regions of transitional temperate climate this impact may include road waterlogging and scouring. Extreme air temperatures can also cause problems for transport. Hot weather softens and deforms asphalt surfaces, while temperatures that drop below zero facilitate the formation of potholes when water alternately freezes and thaws in the dips and hollows of the road surface (Mazur 1998). As for precipitation, given their high frequency of occurrence, the most impactful on the performance of transport are rain and snow. While downpours damage road sections through washouts or scouring (Mazur 1985), snow accumulation is also a major concern. Other weather conditions that pose a great hazard to road transport are black ice and frost. A combination of unfavourable factors such as inadequately maintained roads, poor drainage, heavy precipitation, low winter temperatures or intense temperature rises in spring can lead to frost-heaving and road surface cracking. If left unrepaired,[1] this damage can eventually result in the complete closure of a given section of the network.

Marcinkowski (2006) also mentions debris, mudflows and landslides caused by heavy rainfall. These phenomena are particularly dangerous on slopes and unpaved shoulders. Mass wasting mainly affects road sections running through foothills and mountainous areas. While it is precipitation that "provokes" these dangerous phenomena, they would not have such intense effects without the "favourable" alignment of geographical conditions. A reduction in network capacity due to a partial or complete blockage of a given road section by rockfall or landslide can occur when mass wasting happens above this section. When a given section is located above a landslip, the road embankment is likely to be damaged along its entire cross-section within the stretch of the road affected by mass wasting.

If roads located on slopes have been ill-designed (i.e., without taking into account water run-off and its flow under the embankment), the surface water run-off may lead to erosion and deterioration of the road surface (especially if it is constructed on saturated clay, argillaceous schist or other poorly consolidated rock types). This occurs when water entering the road material exceeds the design limitations of the drainage systems (including ditches, culverts and stormwater sewers, with adjunct infrastructure of separators, retention facilities, etc.) or when these systems become clogged. Any uncontrolled inflow of water can result in groove cutting and saturation of the embankment slope, which, if excessive, can lead to landslides. Waterlogging and erosion of road edges often affect sections running across flat terrain, on valley bottoms, terraces, floodplains, etc. (Forman et al. 2009). If the design of a given road incorporates no adequate drainage system (or it is not implemented later when the road is upgraded), it may pose a threat to its stability, especially in areas where there is strong groundwater action (e.g., where local groundwater systems drain in the immediate vicinity of large river valleys).

Since water and the material it transports represent a threat to road infrastructure regardless of relief or altitude, the fact that in a given area there is no need for extensive land preparation to build a new road becomes its great economic advantage over other locations. Forman et al. (2009) show that damage caused by flooding is the most extreme and severe example of water-related impact on roads in flat areas. Repeated saturation of the roadbed in flat lowland areas can result in road slippage, which is usually accompanied by cracking

[1] Execution of works to restore the original condition of the road, including building materials other than those used originally (Act of 21 March 1985 on Public Roads, Journal of Laws 1985, No. 14, Item 60, as amended).

and destabilisation of the road surface. In addition, a floodwave of a sufficient speed and height can cause damage to embankments, individual sections of bridges or other engineering structures (the impact of flooding is discussed in detail in Subchapter 2.2.3).

The lack of effective drainage on roads (especially those with paved carriageways) can also significantly affect traffic conditions. Examples include loss of tyre grip (aquaplaning) or reduced visibility when spray coming from under the wheels of the preceding vehicle deluges the windscreens of following vehicles (Forman et al. 2009).

Since water (in its various forms) has the greatest impact on the operation of road transport (as shown by a review of studies into natural factors that can adversely affect it), a broad spectrum of regulations, standards, and good practices applied during the design, construction, and maintenance of roads and engineering structures (especially those directly exposed to watercourses) have been implemented to prevent and mitigate the possible negative effects of the actions of water, including flooding. However, Forman et al. (2009) also emphasise that road infrastructure is the "main enemy" of water, and road infrastructure projects today must take ecological issues into account, which makes the design of infrastructure even more challenging.

The list of natural factors that can adversely affect road transport also includes wind, whose destructive action (direct or indirect) is becoming more frequent due to global climate change. Direct action is when strong winds create drag against vehicles in motion, sometimes even overturning them, especially when the road surface hampers grip. Particularly vulnerable are vehicles with a large sidewall area (coaches, tractor-trailers, articulated lorries, etc.) travelling in open terrain, or emerging from a road section that is sheltered from crosswinds to one that is more exposed (e.g., while leaving a wooded area). Strong winds can also have an indirect effect, by blowing various material onto the roads (which often promotes skidding) or damaging vegetation and overhead powerlines, whose debris often falls onto the road surface.

Animals can also impact the smooth functioning of the road network. Besides the rare examples of the actions of animals that can be dangerous for road transport (e.g., beavers felling trees), it is mainly accidents involving animals that cause disruption (Komornicki et al. 2015). From the reverse angle, roads represent a significant barrier for the animal kingdom.

As for threats to the road network which are of anthropogenic origin, those from mining must be mentioned, since it can cause severe damage, especially to paved road sections which are unresistant to deformation. Marcinkowski (2006) lists a fire in the vicinity of the road as yet another phenomenon that can be extremely detrimental to the whole network, as it impairs the useability of the infrastructure by deteriorating traffic conditions, e.g., due to smoke blowing across the carriageway. Moreover, the extreme temperatures or physical damage caused, for instance, by (burning or smouldering) parts of buildings or trees falling onto the road have a degrading effect on the network itself, damaging the surface and other components of the road infrastructure.

Other possible anthropogenic events which may happen on the roads or in their immediate vicinity that cause disruption include aeroplane, car and train accidents, chemical or fuel spills, powerline incidents, leaks from tankers transporting hazardous cargo, spillage of transported chemicals, etc. The list of non-typical events of anthropogenic origin that may disrupt the road transport is expanded with lane closures due to organised roadblocks (possibly connected to strikes or demonstrations), uncontrolled population migration or even acts of terror (Marcinkowski 2009).

It must be emphasised that the factors listed above can affect the operation of road transport directly and indirectly, as the magnitude of the impact depends not only on the nature of the destructive element itself, but also on the location and the time when road transport is affected. Therefore, while it is incredibly difficult to compile an exhaustive list of factors that may impede the operation of road transport, it seems even more challenging if not virtually impossible to identify a comprehensive set of the features and effects of such factors.

The review of non-typical events and the nature of their impact on the efficiency of road transport reveals that segments that run in the immediate vicinity of rivers, along floodplains or in landslide-prone areas that lack appropriate protection (trenches, embankments, etc.) are particularly susceptible to disturbance. This also applies to road segments built in areas susceptible to the effects of mining; located in close proximity to businesses that may have a significant impact on their immediate surroundings (contamination, etc.), or road sections running through woodland (falling trees, etc.) (Marcinkowski 2006).

Non-typical events expose the road transport network (roads and engineering structures) to factors that impede its performance. When these events occur (separately or jointly) and are of sufficient intensity or duration, the robustness of individual network components can be compromised, thereby affecting their serviceability. One can identify three main factors that affect the functioning of the road network: exposure to high temperature, pressure, and above-normal operational load or stress placed on a given road (Marcinkowski 2009). A fire in the vicinity of the road network may scorch and deform the surface, which, in turn, may lead to a reduction in the load-bearing capacity. The destructive effects of pressure may occur during the passage of a floodwave, ice floes or other water-borne debris, or when there is an explosion on a tanker. Exceeding the permissible load of network components can arise from the passage of overweight lorries or an unexpectedly large flow of vehicles following changes in traffic organisation. A reduction in the load-bearing capacity of a given road structure or a loss in its stability may also stem from changes in its foundations or rheological and wear-and-tear factors due to cyclical and long-term load (Marcinkowski 2009).

Those responsible for the functioning of the road network when any of the non-typical events listed above occur should ensure that the infrastructure retains a minimum acceptable level of operability – including designating diversions, if possible, for the closed network sections – and should also ensure that direct and indirect damage is promptly repaired.

2.2. Flooding as a hindrance to transport

Providing an accurate and exhaustive list of transport disruptors is an extremely complex task, mainly due to the multitude of factors that affect the design of transport networks and systems, and their subsequent use. It is therefore necessary to make certain generalisations and classifications in this respect, one example being the division into anthropogenic and environmental causes. While the former are infrastructural, economic, legal-administrative, psychological, and demand-related factors, the latter include physical-geographical (geological, relief, climate, weather, hydrographic, fauna and flora, etc.) and ecological ones (Mazur 1998, Komornicki 1999, Komornicki et al. 2009, Rosik 2012, Wiśniewski 2015, Koziarski 2020). A holistic approach to the determinants of transport efficiency considers land use (spatial component), the transport network (transport component), and the socio-economic traits of the network users (personal component), manifested at a particular point in time (temporal component). The variables within each group of factors allow for the development of a broad spectrum of models and simulations. However, any disruption to the road network is invariably linked to a reduction in the attractiveness of a given trip destination. An unusual event such as flooding can amplify distance decay for a chosen destination, sometimes constituting a strong enough deterrent to make a road network user cancel their journey.

2.2.1. Selected properties of floods in Poland

Pursuant to Article 16 of the Act of 20 July 2017 on Water Law (Journal of Laws 2017, Item 2268). A flood is defined as:

> […] an overflow of water that temporarily submerges land that is usually not inundated, in particular caused by water surges in natural watercourses, reservoirs, canals and from the sea, with the exception of overflows caused by water surges in sewer systems.

There are various classifications of floods in the literature, based on such criteria as scope, magnitude, origin and type of surge (Lambor 1954, Mikulski 1997, Mioduszewski 1998, Byczkowski 2005). These attributes are important for the vulnerability and resilience of the transport system, and they should be taken into account when planning road infrastructure in the areas directly threatened by floods (with particular focus on the robustness and survivability of the road network) and those that may be affected indirectly, e.g., by deferred traffic (with particular focus on the redundancy of the system). Accurate identification of the specific features of the threat is also important for those in charge of ensuring the functioning of the road network, as it will determine the measures they take during a disruption (affecting the adaptability and flexibility of the system, etc.) and before/after a disruption (determining the resourcefulness of the system, etc.). The types of floods presented herein are discussed by their origin and progression, on the basis of the classification proposed by Lambor (1954):

- pluvial flooding – caused by torrential or prolonged rainfall;
- snowmelt flooding – caused by rapidly melting snow;
- storm flooding – caused by severe storms in lagoons or along the coastline;
- winter flooding – caused by the actions of ice, e.g., ice floes (Borowska-Stefańska 2015b) (Figure 2.1).

As shown in both Figure 2.1 and Table 2.1, not only can floods occur throughout the year, but different types of floods can also occur in the same area if several adverse factors (sudden warming, adverse barometric situation, intense precipitation, etc.) act simultaneously. The most common floodings in Poland are inland floods, including pluvial, snowmelt and ice-jam flooding (Kowalewski 2006, Pajewska-Kwaśny 2012). The main cause is torrential, frontal or prolonged rainfall of different severity and scope. The most violent are usually pluvial floods. Another important factor here is whether the flooding is caused by torrential rains, short thermal thunderstorms or frontal rainfall – all aggravated by mountainous terrain. For that reason, Lambor (1954) divides pluvial floods into torrential and prolonged, as they differ in origin and territorial extent, the latter being closely related to the exposure of the road network and the importance of its different components. Torrential rains, mostly due to the interaction of hot and cold air, are localised in both lowland and mountainous areas, which makes the usual range of exposure relatively narrow. And since they accompany thermal thunderstorms, they are most common in summer (July and August).

Although pluvial floods caused by frontal precipitation have a similar effect to floods caused by torrential rains, they have a far greater territorial spread, i.e., they occur throughout Poland. Thus, in this case, the exposure of the transport network is potentially much greater and the importance of its individual components must be assessed on a wider scale. It is also considerably more difficult to ensure the optionality of transport routes, as these can be substantially changed by the way users use the network, thereby changing the importance of individual network segments under “normal” conditions against the expected importance when the network is modelled without load. Prolonged and frontal rainfall in areas of high-intensity precipitation may be exacerbated by orographic structures of the region that experiences this high intensity (e.g., the Sudeten Mountains). For such regions, pluvial floods are exceptionally dangerous, contributing to extraordinary flooding on the Upper Vistula, the Middle Vistula, and the Oder, making this type of flood extremely destructive.

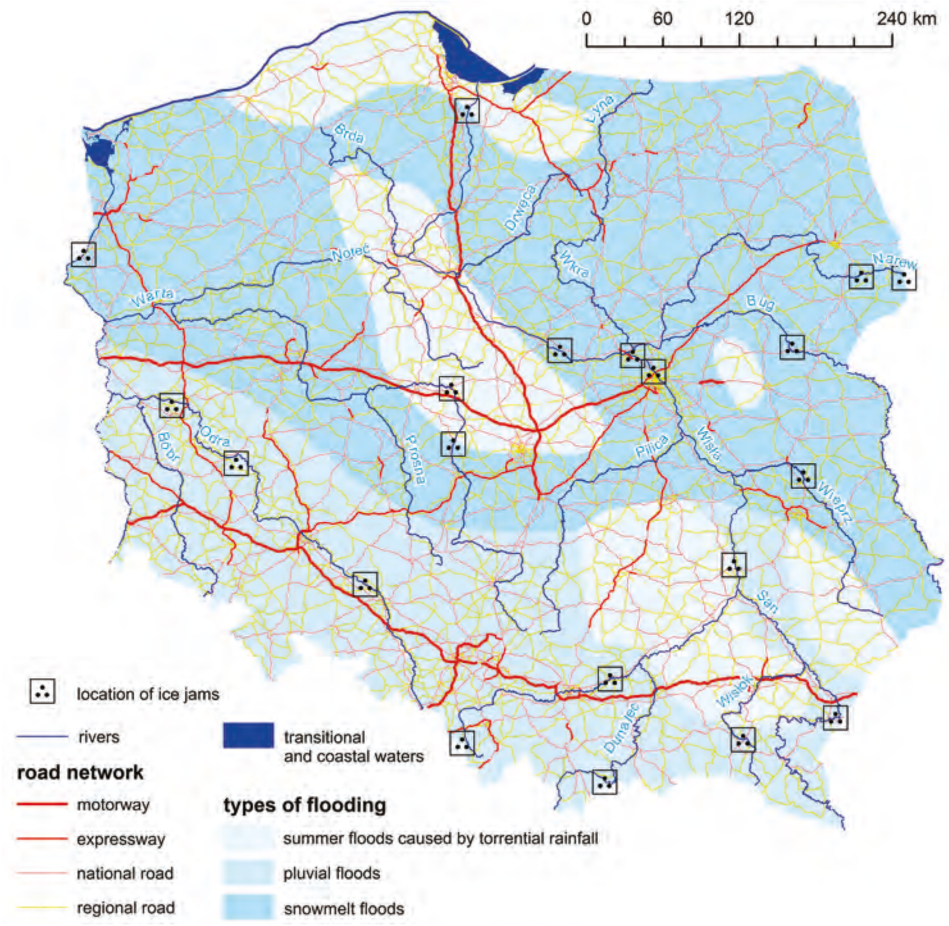

Figure 2.1. Spatial location of various types of floods in Poland by their origin and progression against the background of the road network as of 2019

Source: own elaboration based on Pajewska-Kwaśny (2012)

Snowmelt floods occur due to rapid melting of snow, caused by a sudden and high rise in air temperature, often intensified by heavy rains that accelerate the melting. Snowmelt floods are generally accompanied by frozen ground, which significantly increases the volume of runoff. In small watercourses, these floods can result in catastrophically high water levels. Another significant factor is the downflow of ice floes and its potentially destructive impact, especially on bridging structures.[2] Snowmelt floods are predominantly seen in the central parts of Poland (the Middle Vistula, the Narew, the Bug, the Noteć, and the Warta), mostly occurring in February and March (Starkel 1999, Kowalewski 2006).

Storm floods occur in estuarine sections of rivers flowing into the sea and in coastal depressions. They are caused by strong winds that blow from the sea towards the land, thus impeding the outflow of river waters, and causing damming and subsequent flooding of adjacent areas. Storm floods predominantly occur in winter, especially in January and December, albeit sometimes in summer (Lambor 1954, Kowalewski 2006, Borowska-Stefańska 2015b).

Lambor (1954) divides winter floods into floodings caused by ice jams and shuga. These differ not only in terms of origins and progression, but also location, scope, duration, and accompanying atmospheric conditions. Shuga floods are triggered by the extreme formation of anchor and frazil ice, which clogs the entire cross-section of the river, often damming water to the level of the stopbanks and causing dangerous localised flooding, which typically occurs in December and January. On the other hand, ice jam floods (where obstructions are caused by ice flow) are localised in nature and occur between December and March (Table 2.1). For transport systems, the direct impact of ice on the bridging structures themselves is as important as the effect it has on water levels. If a structure important for a given transport system does not have a sufficiently high level of survivability and robustness, its adaptive capacity may be exceeded. Knowing the susceptibility of the structure, road authorities may decide to pre-emptively shut it down just upon inspection, even if there are no signs of deterioration.

Long-term observations of rivers prove that, besides the genetically homogeneous types distinguished by Lambor (1954), there are also mixed types of floods, e.g., on the coast, where storm floods and surges caused by rainfall, snowmelt or ice blockages overlap (Kowalewski 2006). Labor's definition and classification of floods (Lambor 1954) generally refers to natural hydrological conditions, unchanged by man. Nowadays, however, sources of floods also include dam failures caused by technical defects and overtopping. Other phenomena that exacerbate flood risk include earthquakes, landslides, ice jams, and tidal or storm surges (Stachy et al. 1996).

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[2] Any structure intended to carry a road, a separate pedestrian or pedestrian/cycling path, a wildlife migration route or other type of passageway over an obstacle, in particular: a bridge, viaduct, flyover, walkway, etc. (Ordinance of the Minister of Transport and Maritime Economy of 30 May 2000 on the Technical Specifications for Road Engineering Structures and their Location, Journal of Laws 2000, No. 63, Item 735).

Table 2.1. Classification of floods

No.	Type of flood		Causes	Scope and profile	Incidence period	
					extreme	most frequent
1.	pluvial	torrential	localised torrential rains, thermal thunderstorms	local severe flooding of mountain streams and small watercourses	V–IX	VII–VIII
2.			frontal rains	broad territorial scope	IV–X	VI–IX
3.		prolonged	frontal rains exacerbated by orographic precipitation	prolonged, severe floods originating in mountainous areas	IV–X	VI–IX
4.	snowmelt		rapid melting of snow accompanied by heavy rains when the ground is frozen	wide scope under favourable conditions	XII–III	III
5.	storm		favourable barometric situation	seashore, Vistula Lagoon, Szczecin Lagoon	X–III VII–VIII	XII and I
6.	winter	shuga	a sharp drop in temperature	localised flooding in particularly vulnerable areas	XII–III	XII and I
7.		ice jam	water accumulation due to a blockage caused by ice flow, usually at bridges	localised, dangerous flooding of rivers and streams in areas with impeded ice flow	XII–III	III

Source: Lambor 1954.

In general, floods inflict most damage in southern Poland, in the basins of the Upper Oder, the Middle Oder, and the Upper Vistula. In Poland, summer floods are the most common – both torrential and prolonged. Snowmelt floods, on the other hand, predominate in central Poland, while storm floods are less frequent and occur mainly along the coast, in the Vistula Fens, the Vistula Lagoon, and the Szczecin Lagoon (Kowalewski 2006).

Flooding is deemed among the most frequent and severe natural disasters (Hossain and Davies 2004, Drozdowska and Grabowski 2014). Due to global climate change, extreme events (here: floods) are on the increase, directly affecting technical infrastructure, including transport networks (Alcántara-Ayala 2002, Suarez et al. 2005, Garnaut 2008, Tsakiris, Bellos and Ziogas 2010).

2.2.2. Historical examples of the impact of floods

Floods have affected man since the dawn of time, causing enormous damage and endangering human life. Between 2002 and 2013, floods in Europe claimed 1,000 lives and forced the evacuation of 1.7 million people (Jonkman 2005, Czaban 2008, Jonkman et al. 2008, Radosavljevic et al. 2017, Adamson 2018, Borowska-Stefańska and Wiśniewski 2018, Borowska-Stefańska et al. 2019a).

The impact of floods on the socio-economic development of Poland, including the operation of transport networks (and road networks in particular), is clear from historical data. The first records of floodings come from old chronicles, archives and parish books (Mikulski 1962, 1963, 1997, 1998). The very first cited account is for a flood in 988 (Czaban 2008, Czaja 2010, Borowska-Stefańska 2015b). Much can also be learnt from Chronicles by Jan Długosz.

Regular monitoring of fluctuations in water levels has been conducted since the early 19th century, making it possible to gather precise data on the magnitude of floods (Mikulski 1998, Grela et al. 1999, Czaban 2008). In the early 19th century, twenty dangerous floods occurred in Poland (Tyszka 1954). The greatest floods were those in the years: 1813, 1831, 1854, 1880 (Dubicki 1999). The largest one, as regards both the magnitude of the surge and the territorial scope, was the disaster of August 1813 (affecting areas in Poland, Germany, Czechia, Hungary, amongst others). In Poland, the Upper Vistula, the Middle Vistula, the Dunajec, the Upper Oder, and the Middle Oder all flooded, leading to catastrophic damage, loss of life, destruction of numerous embankments and bridges, and inundating entire towns and settlements (Mikulski 1998, Barczyk et al. 1999, Czaja 2010, Franczak 2014, Borowska-Stefańska 2015b).

In the 20th century, thirty major floods were recorded in the Vistula basin, the largest of which occurred in the years: 1903, 1924, 1927, 1934, 1938, 1947, 1960, 1962, 1970, 1972, 1979, 1980, 1982, 1983, 1997. In the Oder basin, the most severe floods were in the years: 1903, 1924, 1930, 1938, 1940, 1941, 1947, 1953, 1965, 1977, 1985, and 1997. This data shows that floodings in the Vistula basin during the century in question occurred on average every three years, while in the Oder basin – every five years (Maciejewski et al. 2011a, Borowska-Stefańska 2015b).

The pluvial flood of 1903 covered a large part of Poland (the basins of the Oder, the Soła, the Vistula, the Skawa, the Rudawa, the Raba, and the Dunajec). During the intense, week-long rainfall, the cities of Kraków and Wrocław suffered most, while 58 villages and towns were also under water and over 15,000 houses were destroyed. After this disaster, the construction of flood protection infrastructure and river regulation were initiated in Poland (Diemientiew 2018). The flood of 1903 remained the largest flood event in the Oder basin until 1997 (Dubicki 1999). Over 30 years later (in 1934), a major pluvial flood was recorded in the basin of the Upper Vistula, with heavy rainfall recorded in the basins of the Raba, the Skawa, the Wisłoka, and especially the Dunajec. The flooding on the Dunajec, the Raba, and the Vistula caused 55 deaths and the destruction of 22,059 buildings. This flood also proved destructive to road infrastructure, damaging 167 kilometres of roads and destroying 78 bridges. After this disaster, retention reservoirs were built on the Soła and the Dunajec. In 1970, Poland witnessed two great floods: a snowmelt event in the north and a pluvial surge in the Vistula basin. 980 road bridges, several hundred other (urban) bridges, well over 10,000 buildings, and countless road sections were damaged. The death toll was 11. Nine years later, there was a snowmelt flood, which primarily affected the northern part of the country and lasted for over two months. 17,749 buildings and 1,250 bridges were damaged or destroyed, as well as other infrastructure (Diemientiew 2018). Another catastrophic flood was the 1997 surge on the Oder and some of its tributaries, a flood which surpassed all previous events. This pluvial flood affected the basin of the Lusatian Neisse, tributaries of the Vistula (Dubicki 1999, Diemientiew 2018) and impacted almost the entire southern part of the country, killing 55 people, causing huge economic and societal losses. 72,267 buildings, 4,048 bridges (including 304 on national roads and 3,744 on regional roads), 14,433 kilometres of roads (including 1,247 kilometres of national roads and 13,186 kilometres of regional roads), and 612.5 kilometres of embankments were damaged or destroyed (Dubicki et al. 1999, Diemientiew 2018).

In the 21st century, the largest floods that have occurred in the basins of the Vistula and the Oder are those of 2001, 2005 and 2010 (Maciejewski et al. 2011b, Borowska-Stefańska 2015b). At the turn of July and August 2001, a catastrophic pluvial flood affected a vast part of the territory of Poland, with the Vistula basin being the worst affected (e.g., Gdańsk was significantly flooded due to torrential rains) (Diemientiew 2018). In 2010, another calamitous pluvial flood caused human casualties and massive property damage. It was the greatest pluvial flood since 1947 (with the third highest recorded water levels since that date) (Tadeuszewski and Wilczak 2011). It affected 15 provinces, forcing the evacuation of over 14,565 families, destroying 18,598 buildings, damaging 825 kilometres of roads and 1,625 bridges (Biedroń et al. 2011, Borowska-Stefańska 2015b, Diemientiew 2018).

The preliminary flood risk assessment data revealed that in recent years, within the basin of the Vistula, floods have occurred most frequently in the catchments of the Vistula itself, the Wieprz, the Bystrzyca, the Tyśmienica, the Pilica, the Narew, the Biebrza, the Bug, and the Rawka (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Vistula River Basin, 2016). In the basin of the Oder, flooding occurred most frequently (four or more events) in the catchments of the Oder itself, the Eastern Neisse, the Oława, the Barycz, the Orla, the Bóbr, the Kwisa, the Lusatian Neisse (water region of the Middle Oder), the Warta, the Liswarta, the Widawka, the Grabia, the Nieciecza, the Ner, the Prosna, the Mosina Canal, the Noteć (water region of the Warta), the Parsęta, and the Wieprza (water region of the Lower Oder and the coastal strip of West Pomerania) (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Oder River Basin, 2016). In the Pregolya basin, floods are generally localised, the most dangerous in this area being snowmelt floods on the Łyna and the Guber (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Pregolya River Basin, 2016).

The length of damaged and destroyed road sections and the number of affected bridges indicate that the Polish road network has so far been characterised by significant exposure and susceptibility to the destructive impact of floods, validating research into the vulnerability of road transport to the impact of these non-typical phenomena.

2.2.3. Types of impact on road transport

It should be emphasised that reliable (highly resilient) transport systems are valued for their safety (robustness and adaptability), low restoration costs (resourcefulness), competitive travel times, and service regularity (Koetse and Rietveld 2009). Maintaining the smooth flow of traffic is not only essential for logistics, supply chain maintenance, and other business activities, but it is also a matter of concern for transport network authorities and managers (Kordel 2002, 2013; Jenelius et al. 2006).

Road transport is an essential component of the daily life of a modern society (Chen et al. 2007) and whenever its performance is disrupted by external events (here: floods), the negative effects will primarily be felt by its users, who – on losing access to vital destinations (e.g., shops, hospitals) – will notice a significant decline in their quality of life and sense of security. Naturally, not all sections of the road network or road engineering structures are equally critical to the performance of the entire network when exposed to flooding (Balijepalli and Oppong 2014). Therefore, it is vital to assess the susceptibility of transport networks to threats so that contingency plans can be prepared and the loss of system capacity after a flood event can be mitigated (Chen et al. 2007, Kim and Yeo 2016).

As mentioned above, weather conditions are among the factors that affect traffic and road safety the most (Brijs et al. 2008, Antoniou et al. 2013). Prolonged precipitation may lead to floods that can easily damage road infrastructure: culverts, bridges, embankments, etc. This damage may result in road closures or a dramatic deterioration of road capacity (Marcinkowski 2006).

Other detrimental effects that floodwater can have on the performance of road transport may also come from the erosion of riverbeds, including direct damage by fast-flowing floodwaters that pose a great hazard to bridging structures,[3] i.e., scouring of bridge foundations, batter piles near abutments,

[3] Bridges, tunnels, culverts, and retaining structures.

and road embankments. The most effective response to counteract this destructive activity is by implementing preventative measures. Madaj and Wołowicki (2013) recommend building flood control channels; appropriate shaping of riverbeds; and implementing reinforcements at bridge footings and embankments.

Measures for restoring the road transport system to an acceptable state of equilibrium need to be prepared for when flooding has already occurred. During the passage of floodwater, it is essential to prevent water-borne material (parts of trees, debris, etc.) from clogging up bridge or culvert openings as this causes the water to dam up. Proactive protection includes forcing through any debris that accumulates in front of the bridge or culvert. In situations when the surge is already extremely high and threatens to destroy the bridging structure (and all other measures have failed), a breach in the embankment on the section leading to the bridge can be made to release the dammed-up water. This decision should be taken by the relevant authority for whom "eyes on the ground" are vital at such times (Madaj and Wołowicki 2013).

Riverbed erosion (here: scouring) does not always pose a threat to the safe operation of road structures. If it has been anticipated in the construction and, in the case of bridges, the footings have been laid at a sufficient depth, the probability of catastrophic effects drops significantly. However, if the design does not allow for riverbed scour or the velocity of water flow in the engineered bed is greater than the critical velocity for the underlying material, the bed should be reinforced to increase the resilience of the road network structures.

Another result of a flood is the flow of floodwater over the road surface, which can severely deteriorate it, especially if the road is unpaved. Surface runoff from an inclined road surface may result in linear erosion of the road embankment, most often observed outside built-up areas. Floodwater can also seep into cracks in the carriageway, thereby deteriorating the road surface. If sufficiently large amounts of water penetrate into the roadbed, this can cause partial erosion of its structural material (Forman et al. 2009).

In low-lying areas, floodwater often inundates roads for long periods, allowing the base material of the road to become oversaturated, thus leading to instability. In a flooded roadbed, the water fills the spaces between the material and acts like a lubricant, thereby compromising structural integrity. This mainly affects roads when the base material contains clay components. In addition, water standing on the road for prolonged periods (due to a low angle of inclination) can damage its surface. This is exacerbated when a given section is exposed to dense traffic, especially heavy vehicles on roads where the water has recently receded. By far the most severely affected are unpaved roads.

Floods in river valleys can even wash away entire sections of the road. However, the most common effect of flooding in such areas is the above-mentioned scouring, which is the erosion of the riverbed and banks near bridge piers and abutments by the flowing water. Once the floodwaters have receded, these components require inspection and, in some cases, the implementation of repair procedures. However, the vast majority of such infrastructure can still be used safely.

The situation is more complicated for sections of the existing road network located in flat coastal areas exposed to storm surges as they are extremely susceptible to significant and extensive damage, whose repair may be impossible or economically infeasible. If badly damaged, these sections are better replaced with infrastructure that is resistant to this type of impact.

In the immediate vicinity of rivers, roads are usually inundated for only a short period (from a few days to a number of weeks), as the surge re-enters the river once the water level in the riverbed has receded. However, water surges in lakes or wetlands that have no drainage channel are considerably more problematic (Forman et al. 2009). Once the nearby roads are inundated, the floodwaters may remain there at a depth that renders them inoperable for significantly longer periods.

Floods which occur rapidly following a heavy rainfall (especially flash floods) are a major cause of transport disruption (Brown et al. 2014, Pregnolato et al. 2017), necessitating road closures and evacuation from affected areas, thus generating enormous costs. There is also the domino effect of increased fuel consumption, delays and accidents, thereby significantly affecting the efficiency of the transport system (Rakha et al. 2007, Cools et al. 2010). Flooding is expected to increase in the future (Dawson et al. 2016) and be particularly severe for road networks within urban areas, due to the prevalence of impervious surfaces that prevent water infiltration into the soil (Pregnolato et al. 2017).

Flood damage to components of the transport network and the operation of the transport system can be divided into direct and indirect losses. The former result from a direct impact of floodwaters on the road network and its users, while the latter are felt not only in the directly affected regions, but also in areas outside the immediate vicinity of the flood. What is more, the period of their impact may be considerably longer than the flood itself (Merz et al. 2004; Borowska-Stefańska 2015a; Borowska-Stefańska and Wiśniewski 2018). Examples of this type of (indirect) damage include traffic disruption (changes in traffic conditions) or losses resulting from restrictions to traffic generation (occurrence of induced or suppressed traffic) due to damaged or preventively closed infrastructure (Merz et al. 2004, Thieken et al. 2005). Damage can also be divided into two other types – material and non-material damage, depending on whether it can be assessed monetarily. Material damage is easily expressed in monetary units, whereas non-material damage is difficult to put a market value on (Jonkman et al. 2008, Merz et al. 2010). Since direct damage is considerably easier to estimate than indirect damage (Merz et al. 2010), the largest body of literature on the subject focuses on estimating direct material damage (Merz et al. 2004).

In the literature, assessing the impact floods have on the performance of road transport as regards traffic disruptions have previously adopted the following assumptions:

• traffic density and speed (real time, average, effective) on the network or on the individual road segments in question correspond to regional (or national) averages notwithstanding the occurrence of flooding;

• a given road affected by the flood is completely closed when its surface is inundated, regardless of water depth;

• traffic on roads that are open during a flood flows smoothly, but with a slightly reduced maximum speed;

• road and traffic conditions deteriorate because of flooding, but traffic density does not exceed the design capacity of the road;

• traffic conditions used in modelling and simulating the impact of a flood do not take into account cyclical variations, e.g., daily or seasonal;

• the designated diversion routes and the changes (or absence of changes) in driver behaviour that occur following a flood are often established without clear justification (Pregnolato et al. 2017).

These assumptions, however, should always be adapted to the specific properties of the study area, particularly for urbanised areas where traffic conditions are most dynamic. Yin et al. (2016) studied the impact of flooding on the road-street network in Shanghai by identifying sections of the road network that are at risk of flooding and the vehicle flows thereon, based on the results of hydrodynamic modelling. A threshold of 30 cm water depth on the road surface, above which the road is closed to traffic, was applied (following the assumption about the correlation between the water depth and the magnitude of impact on vehicle traffic, as listed above).

Understanding the impact that flooding has on road traffic can help to minimise this impact. However, to enable this, researchers and practitioners need a reliable set of flood data (when one knows which area is likely to be flooded, one can respond to hydrological warnings in a timely manner) – which, in Poland, can be obtained from flood hazard and flood risk maps – and analytical models that can be employed to juxtapose traffic patterns with specific flooding conditions (Rakha et al. 2007). When facing a flood, it is extremely important to properly manage its risk at every stage. For instance, during a flood event, traffic can be managed so that its flows along potentially vulnerable sections of the network are minimised.

Research indicates that there are a number of possible responses to the reduced performance of a transport system affected by the effects of floodwater or the risk of such a deterioration. In some cases, this response may involve modifying technical parameters of key elements of the infrastructure, for instance, by raising its height above assumed maximum flood levels (lowered susceptibility). Sometimes, however, it makes the network more dependent on these key elements (increased importance) and thus more vulnerable should they fail. An alternative approach is to add extra sections to the network (especially alternative routes to vulnerable sections), increasing the redundancy of the network (Taylor and D'Este 2007). This issue is also crucial for safety, as transport systems are critical infrastructure that allows public offices, institutions, and businesses to function efficiently (Ładysz and Ładysz 2010).

2.3. Transport during evacuation

The occurrence of a flood, or its imminence, may result in the initiation of an evacuation process, which affects the performance of the whole transport system. The road network may become congested with traffic generated by evacuees – or transported animals and property – moving from areas at risk to safety or, conversely, intended journeys may be cancelled, leading to a reduction in expected vehicles. The consequences for road transport should therefore be considered both with regard to evacuation-related trips and their impact on the equilibrium of the whole system.

Currently, the assumption that there exists an effective method of total flood protection is eschewed in favour of an approach whereby complete protection is considered impossible and damages and losses can only be mitigated (Schanze et al. 2007). To reduce the negative effects of flooding on the population, the focus should be on maintaining preparedness. This includes warning people about the flood hazard and teaching them the rules of conduct in case it occurs (evacuation guidelines) (Eikenberg 1998, Gunes and Kovel 2000, Plate 2002, Drużyńska and Nachlik 2006, Nachlik 2007, 2008, Sieradzka-Stasiak 2010, Borowska-Stefańska 2015b). Here a clear distinction must be made between the different stages of flood risk management, i.e., flood protection and emergency management. As regards the former, the main goal is to effectively protect the population against the effects of a flood event in a way that prevents water from coming into direct contact with people and property. As for emergency management, the objective is to conduct the flood response as efficiently as possible, focussing on protecting life and health; reducing material losses caused by flooding; maintaining transport efficiency while evacuating people and their property; providing supplies and equipment for damage mitigation; and ensuring those facilities where large numbers of people are expected to gather are safe and secure (Buczek and Nachlik 2011).

The evacuation process is designed not only to protect human life and health, but also to save animals, property (especially from historical sites), and important documentation in the event of a disaster. Evacuation is necessary when the population residing within an area is considered to be in jeopardy and requires transporting to safety (Hsu and Peeta 2014). Although everyone within the areas at risk is subject to evacuation, priority is given to mothers with children, pregnant women, the disabled, patients in care facilities, residents of orphanages and social care facilities, etc. (Barć 2017). The decision to evacuate can be taken at different stages of a disaster; for instance, it can be preventive, so that areas and facilities within the scope of an impending threat are evacuated prior to the incident. Although the goal is for the process to be conducted both quickly and effectively (Richter et al. 2013), it is complicated by the fact that the decision on the best evacuation route is made simultaneously by many people, often with a limited knowledge of the disaster that has occurred.

Evacuation guidelines that take into account dispersion, decentralisation and retreat (Przeworski 2002) and vary in detail can be found in emergency management plans, operational procedures for flood protection, evacuation plans or plans for the accommodation of the evacuated population for a given municipality, district or province. Population evacuation and possible evacuation routes may also be addressed by: reports on the operational preparedness of the (State) Fire Department; rescue plans in the event of a natural disaster; reports on the need for emergency services and resources; and action plans of the provincial police commander for when natural disasters or technical failures occur. Some of these documents precisely stipulate how transport should be organised during the evacuation process. For instance, a handbook prepared for the population of Borne Sulinowo (a town in north-western Poland, within West Pomerania) states that evacuation by road transport should be performed in convoys of up to 10 vehicles travelling at an average speed of 20 km/h. For each motor vehicle, a person responsible for the passengers inside is appointed. The leader of the convoy must know the route and road conditions there, and they should be equipped with a map of the route. The following facilities are to be used to accommodate the evacuees: holiday camps and homes, hotels, dormitories, day care centres, and any other premises deemed suitable for this purpose. If necessary, the evacuees will be accommodated in the homes of the local population (Rules of Conduct for the Population When the Announcement to Evacuate Is Issued – A Guide for Residents, 2016, pp. 2–4).

In the literature there are two major approaches to emergency management during non-typical events (including floods). The first states that all the planning in the world (and the resultant documentation produced) will not bring the hoped for results, while the second claims that more effective planning can improve the level of safety (Cook and Zurita 2016). Some authors state that it is impossible to produce accurate forecasts or effective response plans (Clarke 1999, McConnell and Drennan 2006), with research to improve emergency management being limited to better forecasts and better response plans, usually plans to optimise the transport component (Cook and Zurita 2016). Even if one assumes that such initiatives can never be fully effective (Boin and McConnell 2007), they are still justified if only for two reasons. Firstly, they have a calming effect on the population in the affected areas (Clarke 1999, Kendra and Wachtendorf 2003), and secondly, by relying only on long-standing emergency response plans, those responsible may become less vigilant and more complacent. Moreover, the implementation of up-to-date preventive measures may also suffer if those in charge believe that there is already an effective emergency management plan in place.

Pursuant to the instructions for evacuation of persons, animals and property in the event of a major hazard issued by the Head of the National Civil Defence (2008), three evacuation stages are distinguished depending on the nature and consequences of the process. Stage I is performed immediately after the occurrence of a sudden and imminent threat to life, health and property (explosions, technical failures, chemical incidents, etc.). Stage II involves previously-planned relocation of the population, animals and property from territories at potential risk. In this case, the decision is made when signs of the threat appear. Stage III is a process conducted on the basis of previously-prepared plans, when an elevated level of national defence preparedness is necessary in response to a national security threat (a war, etc.). As regards floods, Stage II is applicable. Since the evacuation process may be initiated at different stages of the disaster (when it is highly likely to occur, or when it has already occurred), its timing will determine how the transportation of evacuees is organised, and how traffic conditions on the local transport network will be affected (Esm et al. 2010).

Irrespective of the decision timeline on evacuation, a key factor is to take into account the population's ability to self-evacuate (Czerechowski 2015), by leaving the areas where an imminent threat may occur or has occurred using primarily their own resources, including private means of transport. Depending on whether there is an impending risk of a floodwave or actual flooding has occurred, the evacuation of the population at risk may differ slightly in form. Evacuation can be either self-evacuation (planned or ad hoc) or an institutionally planned process (Rawłuszko 2016). Planned (organised) self-evacuation occurs when populated areas have not yet been inundated but flooding is likely. Residents in this case can self-evacuate once advised to do so or on the basis of their own observations of the progress of the flood. Their own means of transport will most often be used. If a household does not have access to a car or other means of transport, their evacuation may require the local emergency services to provide them with a suitable means of transport or to enlist the assistance of neighbours. Ad hoc (spontaneous) self-evacuation takes place when there is an imminent threat of flooding, and the population is required to self-evacuate immediately using their own modes of transport. By contrast, planned (organised) evacuation by a relevant governmental body is a prepared relocation of the population at risk when there is a potential threat to them and their property. Once the decision to evacuate has been made, it will become necessary to provide transport to take evacuees from the danger zones to safety. This should take into account not only the evacuees' own modes of transport, but also other vehicles (e.g., people carriers, vans, and lorries available in a given municipality), and evacuation on foot (Rawłuszko 2016).

Instructions prepared by the National Civil Defence also emphasise the importance of the evacuees' own cars in the process of evacuation, stating that this mode of transport is primary in the planning and execution of evacuation. It is therefore crucial to understand the possible scale of self-evacuation and to identify its possible directions and routes, as well as to ensure access to fuel and technical support along these routes. When evacuees travel using their own means of transport, evacuation management is limited to indicating recommended directions, (evacuation) routes and destinations. As a rule, evacuation should be conducted within a given administrative unit (depending on the scale of the disaster, this could be a given municipality, but also the entire province). In line with Stage II evacuation guidelines, evacuation routes are to be designated. While evacuation plans at the provincial level should clearly designate evacuation routes for both those who self-evacuate and those who are to be evacuated, at the district and municipal levels, specific roads should be designated for the evacuation of the population. When devising evacuation plans, a one-size-fits-all model should not be adopted for different types of hazards (Ogrodniczak and Ryba 2015). When considering the scope of an evacuation, the ability to use private means of transport should be taken into account as well as the guiding principles of traffic management and its organisation (Czerechowski 2015). For instance, in the event of a flood, buses are not used to evacuate the population from inundated areas, as this is logistically impossible: there are too many people who are often scattered around the affected area.

The additional traffic flow generated by both planned and ad hoc self-evacuation affects the equilibrium of the transport system, especially when faced with already executed closures of sections of the road network (e.g., due to threats of flooding or damage to structural stability). Naturally, self-evacuation must not be the only method of relocating people from a danger zone to safety (Gromek et al. 2014). It is also necessary to provide transport for those people who are elderly, vulnerable – especially those with limited mobility – or incarcerated, as they may not be able or allowed to self-evacuate (Gromek 2014). Self-evacuation may also constitute a significant barrier to the evacuation of vulnerable people due to the overloading of road capacity (Lumbroso et al. 2008). The number of secondary hazards that local communities may experience when being evacuated include road accidents and collisions or exceeding the capacity of the road transport system during the evacuation (Gromek 2015).

As shown in a pilot study conducted at the Institute of the Built Environment and Spatial Policy at Łódź University on a group of 500 households within those areas at a 1% probability of flooding, experience of a flood in the past affects the population's awareness of evacuation procedures (Figure 2.2).

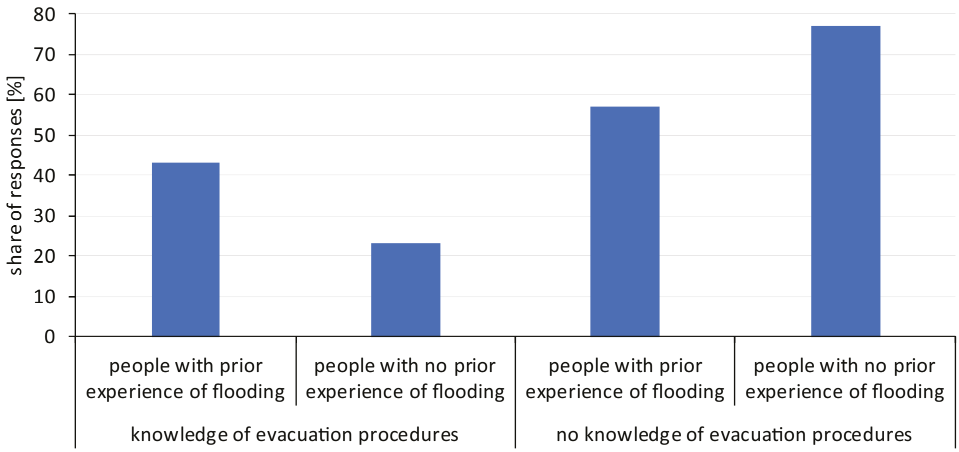

Figure 2.2. Correlation between experience of flooding and knowledge of evacuation procedures among the population living in areas at a 1% probability of flooding in Poland in 2020

Source: own elaboration

This corresponds with the conclusion presented in the Flood Risk Management Plan for the Basin of the Vistula River (2016), whose authors claim that the most effective impetus for flood protection awareness is the population's own experience or the so-called "generational memory." Passing information from generation to generation usually results in an acceptable understanding of the appropriate transport behaviour during evacuation. The experience of flooding also teaches residents how to protect themselves against loss and damage. A very positive picture of the population-at-risk's awareness of evacuation routes emerges from the said pilot survey. As many as 83% of respondents indicated that they knew which route they should take and to which destination to go should it be necessary to leave their homes due to a threat, with 60% stating that they would head for the designated shelters (schools, day care centres, etc.).

Members of one in three households will have the option to head to family or friends residing outside the affected areas. Almost 70% of the households surveyed are ready (49% declare strong preparedness) to undertake self-evacuation. Considering only firm declarations, the results are almost identical to those obtained by Gromek (2014) and Gromek et al. (2014). However, as the authors justly stress, these are only declarative results which can change dramatically once the real perception of the threat arises. The impact of self-evacuation on the transport system as a whole should also be taken into account given the declared mode of transport. If it is assumed that evacuation will be conducted primarily by evacuees' own cars, the flow of vehicles heading to a single destination may create bottlenecks on the road network. As many as 84% of journeys would be made by own car (only 5% of households have no car). There is also a very low percentage (12%) of households where emergency services would be required (e.g., due to the residents' vulnerability).

There is a large number of works in the literature on evacuation in the context of transport organisation, a thorough review of which has been compiled by Murray-Tuite and Wolshon (2013), among others. Some studies only consider evacuation with regard to the accessibility of evacuation sites for evacuees (Borowska-Stefańska et al. 2017), while others focus on the evacuation process itself taking into account only the departure of the population from the areas at risk. For instance, in line with the Critical Cluster Model (CCM), Church and Cova (2000) presented a methodology indicating those areas where the issue of having to transport a large population during an evacuation using a road network of low capacity may arise. To determine the time required to evacuate a given location (a housing estate), they employed data on the evacuees (the number of homes and the average number of residents per home), the number of vehicles at their disposal, and the capacity of the roads serving traffic from the affected area. Chen et al. (2012) included the Critical Cluster Model in their study of evacuation, applying Dijkstra's algorithm to do so. Borowska-Stefańska et al. (2020a) introduced the A* algorithm for this purpose, while Shahabi and Wilson (2014) proposed modelling evacuation in urban transport networks by the CASPER algorithm. Richter et al. (2013) observed that decentralisation of evacuation management can yield good results, and Yuan et al. (2017) focused on simulating traffic during evacuation based on a multilevel decision-making model.

Uno and Kashiyama (2008) and Chen et al. (2012) were among those who attempted to build a model simulating evacuation from at-risk areas. They employed Dijkstra's algorithm to determine evacuation routes, where the distance represented the weights on the edges of the graph. By contrast, Borowska-Stefańska et al. (2019b) adopted the Dinitz, Edmonds-Karp and Ford-Fulkerson algorithms (Goldberg and Tarjan 1988, Ford, and Fulkerson 2015) to determine evacuation routes. Broadly speaking, these algorithms are applied to determine the largest flow obtainable in a non-cyclic directed graph. They can also be used to study congestion (Abdullah and Hua 2017) and road capacity, including analyses that take into account the optimum speed of vehicles to maximise capacity (Moore et al. 2013). Liu et al. (2006) utilised the Adaptive Evacuation Route Algorithm (AERA) for this purpose. Kongsomsaksakul et al. (2005) proposed a methodology for determining shelter locations optimum for the organisation of transport when planning flood-related evacuation.

When addressing the optimisation patterns of planned evacuation, one should also take into account the vulnerability of the transport system (Adger 2006), which is particularly relevant as regards the human factor (Simonovic and Ahmad 2005, Strang 2013). Here, an undeniable challenge is to determine the susceptibility of individual "actors" of an evacuation by establishing trusted and reliable data sources and incorporating a variety of methods that assess risk perception and susceptibility (Pel et al. 2010). Among the methodological approaches to this issue, one should note agent-based modelling (ABM) (Wang et al. 2016), which relies on the development of agents whose attributes determine their current status and who make spatial decisions and can exchange information with each other. This allows the researcher to incorporate the element of randomness into the model, which is essential in naturalistic observation (Chen et al. 2006, Chen and Zhan, 2008, Samuels et al. 2009, Priest et al. 2011, Dzieszko et al. 2013, Tagg et al. 2016). What is also crucial for the effective modelling of the evacuation process is to grasp the circumstances under which individuals at risk decide to evacuate (Dash and Gladwin 2007, Du et al. 2017). According to Southworth (1991), Murray-Tuite and Wolshon (2013), and Sun, Zhang and Su (2020), transport behaviour in this regard is influenced by their level of confidence in the evacuation instructions; their perception of risk; the stage at which the decision (in psychological terms) to leave the area at risk is made. Here, Laska (1990) lists four phases: anxiety, recognition of danger, acceptance, and decision to evacuate.

Such factors as the range of methodological approaches, the diversity of the transport network, the spatial distribution of the population at risk and places of safety, and above all, the considerable unpredictability of people's behaviour, e.g., anarchic evacuation (Masłowska-Szczerba 2015) mean that research into the organisation of evacuation-related transport appears to be justified only when local conditions and the local spatial scale are taken into account. Making universal assumptions in this regard could excessively skew the results obtained.

3

FACTORS IMPACTING THE OPERATION AND DEVELOPMENT OF THE ROAD NETWORK IN FLOOD HAZARD AREAS

3.1. Flood hazard areas and selected characteristics

Although nine river basins have been designated in Poland, flood hazard maps, flood risk maps, and flood risk management plans have only been produced for three – the basins of the Oder, the Vistula and the Pregolya (Figure 3.1) (https://warszawa.wody.gov.pl/). As a result of this omission, the simulations conducted of the effects of flooding on road transport were based on data for these particular regions. Any delimitations applied in this regard were also taken directly from the above-mentioned flood documentation. Among all the scenarios included on the flood hazard maps, this study only focuses on areas with a high probability (10%) and medium probability (1%) of flooding (both fluvial and coastal), and those areas at risk of flooding due to a complete breach of stopbanks (SB) or the protective structure of the service strip (SSB). The occurrence of a 100-year flood is not only the most frequently addressed scenario in the literature, but it is also the only one included in Polish legislation governing land use planning, including that for road infrastructure. Obviously, areas at risk of a 10-year flood (the highest probability) are included in the analyses of those at risk of a 100-year flood. Although the complete breach of a stopbank or the protective structure of the service strip are less realistic scenarios (their probability is not determined), the 1% flood was taken into account when modelling the extent of areas at risk of this type of flooding. The inclusion of stopbanks and the protective structure of the service strip in the study was justified by the fact that there was a need to analyse the vulnerability of the road transport system to non-typical events, the nature and location of which are not always taken into account during planning and construction.

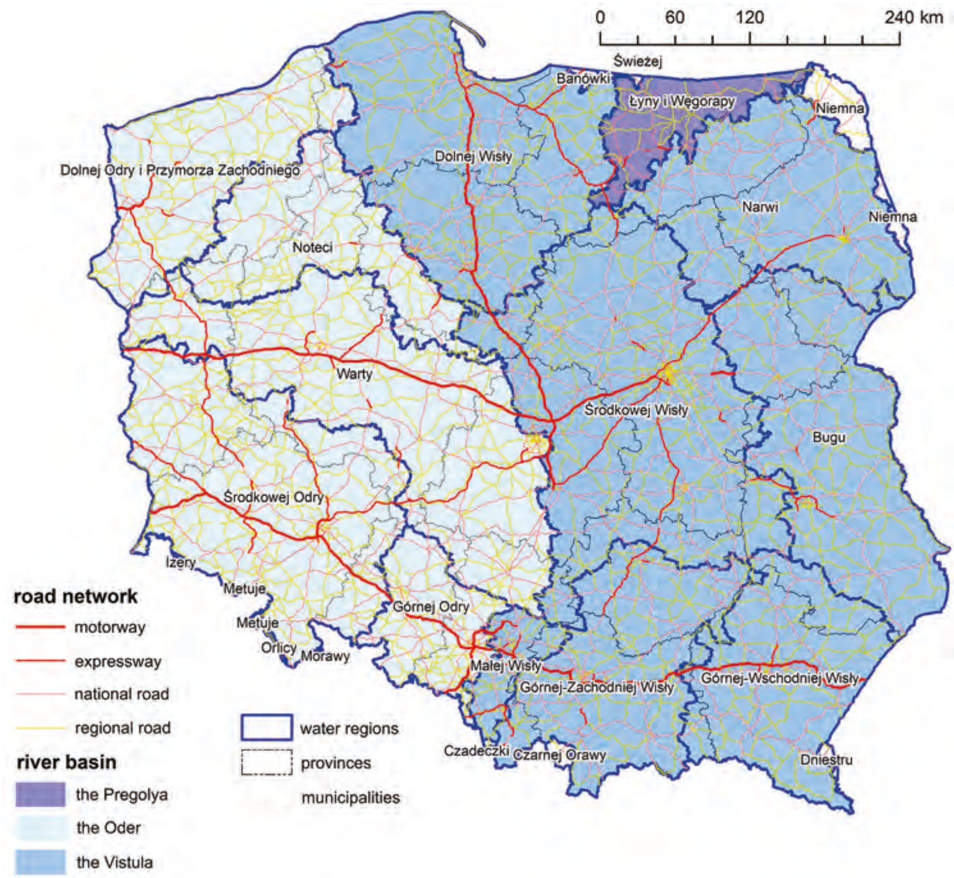

Figure 3.1. Division of Poland into river basins against the road network in 2019
Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

The largest flood hazard areas are reported in the basin of the Vistula, which pertains to both areas at elevated risk of flooding and those at risk of flooding due to a complete breach of a stopbank or the protective structure of the service strip (Table 3.1). The basin of the Vistula is vast, stretching across the northern, north-eastern, eastern and south-eastern regions of Poland and covering 183,000 square kilometres (59% of Poland's territory). Administratively, the basin is located within eleven provinces: Silesia, Lesser Poland, Subcarpathia, Lublin, Świętokrzyskie, Łódź, Masovia, Podlasie, Warmia-Masuria, Kuyavia-Pomerania, and Pomerania. Apart from the direct catchment area of the Vistula, the said basin includes the catchment areas of other rivers flowing into the Baltic Sea (the Słupia, the Łupawa, the Piaśnica, the Łeba) and those feeding the Vistula Lagoon (the Pasłęka, the Bauda, the Elbląg). A distinctive feature of the Vistula basin (as well as the Oder basin) is its pronounced asymmetry, with a predominance of right-sided tributaries caused by land inclination across the North European Plain.

Major left-bank tributaries of the Vistula are: the Przemsza, the Prądnik, the Nida, the Kamienna, the Iłżanka, the Radomka, the Pilica, the Bzura (together with the Rawka), the Brda, the Wda, and the Wierzyca, while the right-bank tributaries include: the Soła, the Skawa, the Raba, the Dunajec, the Wisłoka, the San, the Wieprz, the Świder, the Narew (with its tributaries: the Bug, the Biebrza, the Wkra), the Skrwa, the Drwęca, and the Osa (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Vistula River Basin, 2016).

The drainage basin of the Vistula exhibits a nivial-pluvial recharge regime with one maximum and one minimum water level per year (Dynowska 1994). Nivial recharge, which generates a maximum water level in early spring and a minimum in the summer-autumn period, is typical of large lowland rivers. The most common floods in the area are pluvial and snowmelt floods, and storm (coastal) floods that occur only in the water region of the Lower Vistula. The Vistula basin is divided into seven water regions: the Lower Vistula, the Narew, the Middle Vistula, the Bug, the Upper Western Vistula, the Upper Eastern Vistula, and the Little Vistula (Figure 3.2) (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Vistula River Basin, 2016).

The Oder River basin is the second largest in Poland (118,000 square kilometres, 38% of the total territory). It stretches across the western part of the country and is divided into five water regions: the Lower Oder and the coastal strip of West Pomerania, the Noteć, the Warta, the Middle Oder, and the Upper Oder (Figure 3.3). Administratively, it lies within nine provinces: Silesia, Opole, Lower Silesia, Łódź, Kuyavia-Pomerania, Greater Poland, Lubusz, West Pomerania, and Pomerania. Besides the Oder itself, it also includes the river basins of the Rega, the Parsęta, the Wieprza, and other watercourses flowing into the Baltic Sea, to the west of the estuary of the Słupia, as well as rivers flowing into the Szczecin Lagoon. Within the Oder basin, floods mainly occur between May and October. They are most frequently observed in the water regions of the Middle Oder, the Warta, the Lower Oder and the coastal strip of West Pomerania. The greatest floodings were recorded there in the years: 1903, 1979, 1997, and 2010 (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Oder River Basin, 2016).

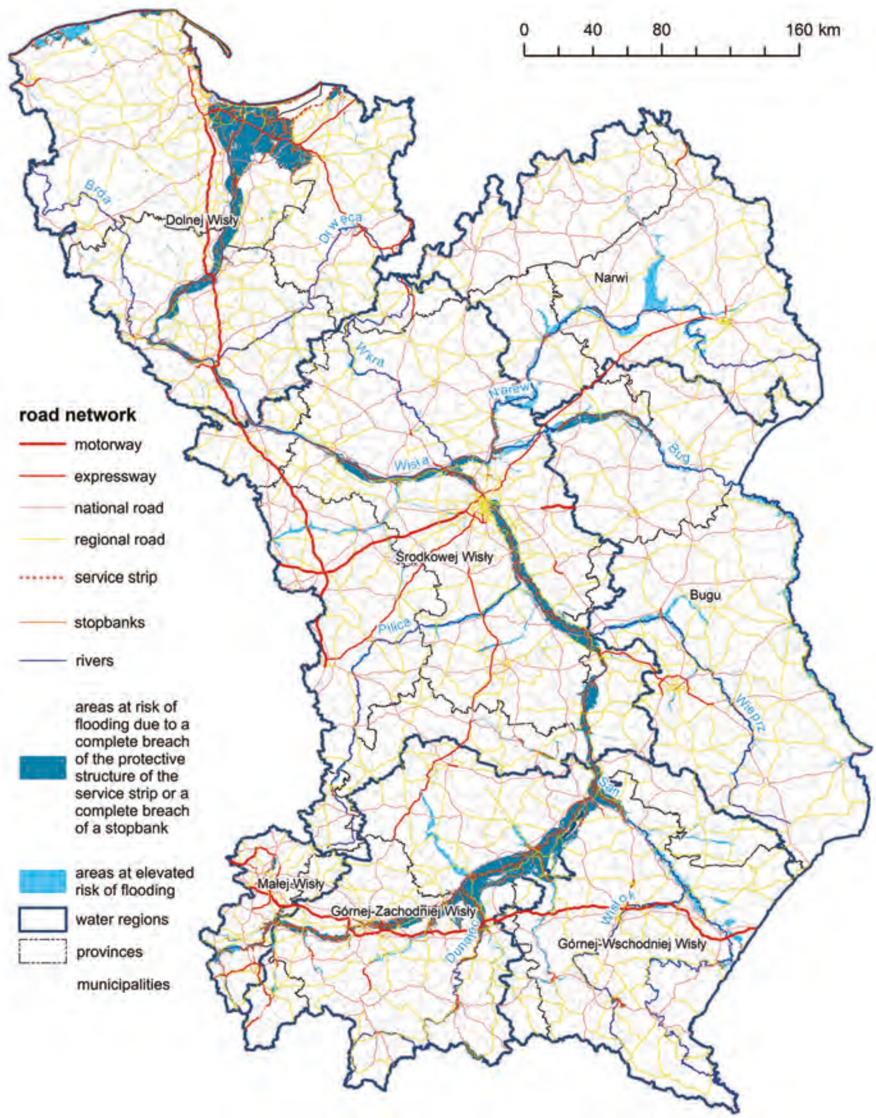

Figure 3.2. Division of the Vistula basin into water regions against the background of administrative division and road network in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

Figure 3.3. Division of the Oder basin into water regions against the background of administrative division and road network in 2019

Source: own elaboration based on data from flood hazard map and flood risk maps by the State Water Holding Polish Waters (2019)

The last river basin for which flood hazard areas were mapped is the basin of the Pregolya,[1] covering an area of 7,521.7 square kilometres in north-eastern Poland (2.5% of the country's territory). Administratively, it lies within Warmian-Masurian Province (Figure 3.4), except for a small section in the north-east located within Podlaskie Province. The basin includes the Pregolya and its tributaries: the Łyna, the Guber, the Gołdapa, the Wadąg, and the Sajna. The largest river within the Polish territory of the Pregolya basin is the Łyna (total length: 289 km; the length within Poland's borders: 208.75 km). There is only one water region there (of the Łyna and the Węgorapa) and the floods observed there are of a localised nature, mainly pluvial and snowmelt (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Pregolya River Basin, 2016).

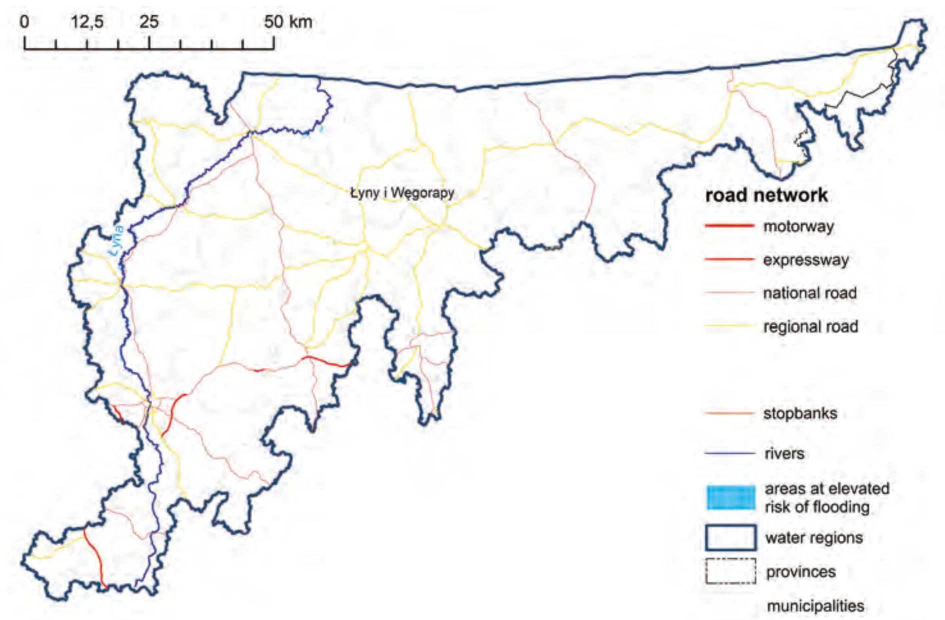

Figure 3.4. The Pregolya basin against the background of administrative division and road network in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

[1] In line with the physico-geographical regionalisation by Solon et al. (2018), the Pregolya River basin comprises two macro-regions: Masurian Lake District and Old Prussian Lowland.

Table 3.1. The surface area of lands at risk of flooding in Poland by river basin in 2019 [ha]

Flood scenario	**Surface area of lands at risk of flooding [ha]**		
	the Oder basin	**the Pregolya basin**	**the Vistula basin**
10%	235,228.60	1,623.66	359,141.64
1%	364,824.70	1,977.77	509,899.33
1%C	30,368.40	–	30,445.70
SSB	14,555.21	–	97,434.32
SB	280,796.14	–	516,681.44

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019).

In the district of the Vistula basin,[2] the largest areas at risk of flooding with a 10% and a 1% probability of occurrence are found in the water region of the Middle Vistula, while areas at risk of flooding due to a complete breach of the stopbank are in the water region of the Lower Vistula. The water region of the Middle Vistula stretches across the central-western part of the Vistula River basin. The floods observed there are caused by thawing (snowmelt), and are often fuelled by ice jams and rainfall. There are also pluvial floods, mainly in summer (mostly July, less common in June and August). The water region of the Lower Vistula spans the northern part of the Vistula basin and suffers not only storm floods, but also ice-jam, pluvial and polder-type fluvial floods (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Vistula River Basin, 2016). Areas at risk of coastal flooding of a medium probability of occurrence and areas at risk of flooding due to a complete breach of the protective structure of the service strip are found only within the water region of the Lower Vistula (Table 3.2).

[2] In line with the physico-geographical regionalisation by Solon et al. (2018), the Vistula River basin comprises the following macro-regions: Wooded Carpathians (Beskids), Central Beskids, Tatra Mountain Range, Orava-Podhale Depression, Western Beskids, Oświęcim Basin, Western Beskidian Foothills, Central Beskidian Foothills, Oversian Basin, Sandomierz Basin, Kraków Gate, Kraków-Częstochowa Upland (Polish Jura), Silesian Upland, Nida Basin, Przedbórz Upland, Kielce Upland, Lublin Upland, Roztocze, Pobuż Basin, Volhynian Upland, Volhynian Polesie, Western Polesie, South Podlaskie Lowland, South Masovian Ridge, Central Masovian Lowland, Greater Poland Lake District, Toruń-Eberswalde Urstromtal, Chełmno-Dobrzyń Lake District, South Masovian Lowland, North Podlaskie Lowland, Masurian Lake District, Lithuanian Lake District, Lover Vistula Valley, South Pomeranian Lake District, West Pomeranian Lake District, East Pomeranian Lake District, Iława Lake District, Old Prussian Lowland, Gdańsk Coastal Strip, Koszalin Coastal Strip, and parts of: Woźniki-Wieluń Upland and South Greater Poland Lowland (Solon et al. 2018).

Table 3.2. The surface area of lands at risk of flooding in Poland by water region in 2019 [ha]

River basin	Water region	Flood scenario				
		10%	1%	1%C	SSB	SB
the Oder	the Lower Oder and the coastal strip of West Pomerania	26,059.70	30,250.10	30,368.40	14,555.21	15,873.30
	the Noteć	26,471.80	39,389.40	–	–	12,914.00
	the Warta	75,341.30	101,169.50	–	–	99,659.40
	the Middle Oder	90,382.10	157,914.80	–	–	139,786.40
	the Upper Oder	16,973.60	36,101.20	–	–	12,563.04
the Pregolya	the Łyna and the Węgorapa	1,623.66	1,977.77	–	–	–
the Vistula	the Lower Vistula	50,496.60	61,323.90	30,445.70	97,434.32	18,8478.20
	the Narew	52,947.40	77,771.80	–	–	1,805.98
	the Middle Vistula	104,407.40	142,189.50	–	–	10,7817.40
	the Bug	59,181.00	79,672.70	–	–	18,646.00
	the Upper Western Vistula	51,607.70	63,196.30	–	–	152,725.73
	the Upper Eastern Vistula	34,778.46	75,684.20	–	–	37,653.97
	the Little Vistula	5,723.00	9,015.30	–	–	9,539.32

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019).

In the district of the Oder basin,[3] the largest areas at risk of flooding with a 10% and a 1% probability of occurrence, or at risk of flooding due to a complete breach of stopbanks are found in the water region of the Middle Oder. The main source of flooding there is prolonged rainfall, however, snowmelt and ice-jam floods are also recorded. Areas at risk of coastal flooding of a medium probability of occurrence and areas at risk of flooding due to a complete breach of the protective structure of the service strip are found only within the water region of the Lower Oder and the coastal strip of West Pomerania (Table 3.2). The area

[3] In line with the physico-geographical regionalisation by Solon et al. (2018), the Oder River basin comprises the following macro-regions: Eastern Sudetes, Silesian Lowland, Silesian Upland, Ostrava Basin, Western Beskidian Foothills and Western Beskids, Woźniki-Wieluń Upland, Sudeten Foothills, Central and Western Sudetes, Western Sudeten Foothills, Silesian-Lusatian Lowland, Trzebnica Embankment, Milicz-Głogów Depression, Lusatian Border Ridge, Lusatian Depression, Zielona Góra Ridge, South Greater Poland Lowland, Greater Poland Lake District, Leszno Lake District, Warta-Oder Urstromtal, Lubusz Lake District, Szczecin Coastal Strip, Toruń-Eberswalde Urstromtal, and parts of: Koszalin Coastal Strip, West Pomeranian Lake District, South Pomeranian Lake District, Kraków-Częstochowa Upland (Polish Jura), Przedbórz Upland, South Masovian Ridge, and Lower Lusatian Depression.

is mainly affected by coastal, ice-dam and snowmelt floods (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Oder River Basin, 2016).

In the event of a flood in the Vistula basin, three areas can be distinguished where possible damage would be most severe. These are the Upper Vistula Valley, the Middle Vistula Valley from Zawichost to Płock, and the Lower Vistula Valley from Toruń to the estuary section of the Vistula, where a significant threat exists in the low-lying areas of the Vistula Fens. This is due to the extent of these valley sections, e.g., the Upper Vistula Valley from Oświęcim through Kraków to Sandomierz and Zawichost is many kilometres wide.

The floodplains are also wide in areas where the Vistula is joined by its right-hand tributaries: the Soła, the Skawa, the Raba, the Dunajec, the Wisłoka, and the San. The largest left-hand tributaries in the Upper Vistula include the Nida and the Czarna Staszowska. However, it is the catchments of the right-sided Carpathian tributaries that mainly fuel flooding in the Upper Vistula, as the deeply incised valleys and low permeability of the subsoil result in significant surface run-off. The floodplain of the Vistula and its tributaries reaches a width of 2.5–6 km in the Oświęcim Basin at the mouth of the Soła, 1–4 km in the narrowing of the Kraków Gate, and from 5.5 to up to 14 km in the Sandomierz Basin at the mouth of the Dunajec.

The Middle Vistula Valley, which begins below Puławy, cuts through almost flat uplands composed of glacial tills or glaciofluvial sands and gravels. A distinctive feature of this part of the Vistula (which increases flood hazard) is the vast basin of the Masovian Lowland in its central part, where the largest tributaries of the Vistula converge, and where the highly developed sprawl of the city of Warsaw is located. The width of the Vistula Valley from Puławy to Warsaw reaches a maximum of 17 km (below the confluence of the Vistula with its right tributary, the Wieprz), more than half of which is made up of floodplains. The floods that occur there are mainly due to the passage of floodwaves that rise in the Upper Vistula. The floodwave is backed up as it flows into the narrowing of the Lesser Poland Gorge of the Vistula and poses a threat to a number of towns and villages located between Zawichost and Puławy.

The Lower Vistula stretches across the northern part of the Vistula basin, from the mouth of the Narew to the mouth of Gdańsk Bay (the Baltic Sea). The lower section of the Vistula Valley below Włocławek and Toruń is an extremely wide floodplain. The flood hazard in this region is affected by the Włocławek Reservoir. This was built in 1970 as part of the planned Lower Vistula Cascade, which, alas, to this day remains the only part of this project completed. As a result of this, severe and deep riverbed erosion is recorded below the reservoir. However, since the floodplain of the Vistula Valley has been drained for several dozen kilometres below the dam, the frequency of floods has decreased, and large areas in the valley bottom have been converted into arable land. Below the forested Toruń Basin (near Bydgoszcz), the Vistula leaves the low-lying Toruń-Eberswalde Urstromtal and flows north, forming its estuary. Initially, it enters the Fordon Valley, which varies in width from approximately 3.5 km (near Fordon) to 10.5 km in the Unisław Basin. Then the river enters the Grudziądz Basin, where the width of the floodplain reaches 7 kilometres, with high embankments protecting a number of villages located in the valley bottom.

The estuarial section of the Vistula Valley is formed by the extensive delta of the Vistula Fens, with a landscape that is unique not only in Poland but also in Europe: forestless plains interspersed with a dense network of channels, ditches, and watercourses. A significant part of the region is made up of low-lying areas. Many rivers, including the Elbląg, the Szkarpawa, the Tuga, the Tyna, the Fiszewka, the Balewka, the Nogat, and canals that have significant heritage, e.g., Elbląg Canal and Jagiellonian Canal run through the Vistula Fens.

The area is unique, mainly due to the polderisation process that has taken place in the delta of the Vistula for 600 years. Natural conditions have been altered through the use of irrigation, drainage systems, and other human activity in the region. Polder water-drainage systems include dykes, dewatering pump stations, irrigation dyke sluice gates, canals, a network of ditches with sluices, etc. The High Vistula Fens, where the altitude ranges from 2.5 to 10 metres above sea level, are served by (passive) gravity systems, which operate without active human involvement, allowing water to drain freely. The low-lying areas of the Low Vistula Fens, with altitudes ranging from 1.8 to 2.5 metres above sea level, are covered by controlled drainage ditches and irrigation systems that allow for modification of hydrological conditions there (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Vistula River Basin, 2016; Borowska-Stefańska et al. 2020b) (Figure 3.5).

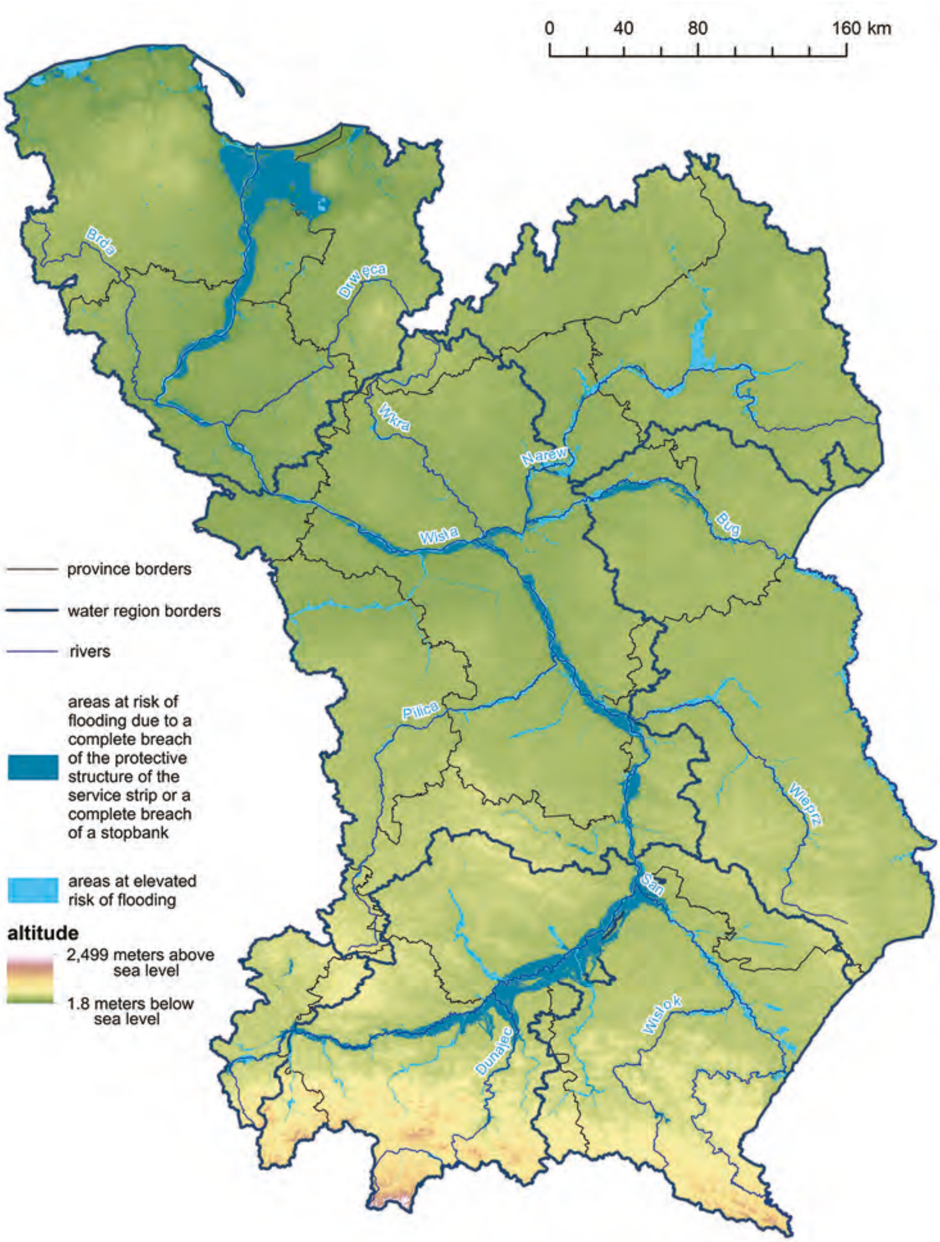

Figure 3.5. Flood hazard areas against the background of the topographical relief in the basin of the Vistula in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Digital Terrain Model by Head Office of Land Surveying and Cartography (2019)

In the Oder Valley, the two regions most vulnerable to flooding and flood-related damage are the Upper Oder and the Middle Oder. In general, the catchment area of the Oder is highly variable geologically with numerous formations of different origin and lithological structure. Although prolonged rainfall is the most common cause of flooding in the Upper Oder, where the largest left-bank tributary is the Psina and the right-bank tributaries include: the Olza, the Rudawka, the Bierawka, and the Kłodnica, short torrential rains also contribute to flash floods there, which mainly applies to the upper tributaries of the larger rivers (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Oder River Basin, 2016). Localised, flash floods occur throughout the Carpathians almost every year (Bryndal 2014). Flash floods are among the shortest and most dramatic hydrological events, characterised by remarkably rapid concentration and short duration of the surge, and the intense mass wasting that frequently accompanies them (Pociask-Karteczka and Żychowski 2014). After Wrocław, the width of the Oder floodplain ranges from 2.5 to over 10 km. A place of special concern in this respect hydrographically is where the Stobrawa (a right-hand tributary) flows into the Oder and the Nysa Kłodzka joins the Oder from the south, on its left side. This is where the floodplain extends for as many as 11 kilometres. In Wrocław, the Oder Valley is at its widest where the Widawa (right-bank tributary) and the Oława (left-bank tributary) meet, and the floodplain stretches up to 7 kilometres. Over half of the city's districts are located within the floodplains of these rivers. The Oder Valley also reaches a spectacular size below the mouth of the Barycz near Głogów (part of the Baruth-Głogów Urstromtal), where the bottom of the ice-marginal valley stretches as wide as 13.5 kilometres (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Oder River Basin, 2016; Borowska-Stefańska et al. 2020b) (Figure 3.6).

The last glaciation was instrumental in shaping the present geomorphological structure of the Pregolya basin. The Scandinavian Ice Sheet left behind a young-glacial relief, the dominant features of which are ice-marginal landforms, areas of ground moraine, and outwash plains. Another distinctive property of the landscape are its numerous depressions, where a rich network of watercourses has emerged. These depressions are usually accompanied by Holocene plains, usually comprising low-moor peats. The longest river in the area is the Łyna, whose upper section flows through a number of lakes in a deep valley. Between the villages of Ruś and Bartąg, the Łyna Valley widens considerably and becomes marshy, although it is regulated around Olsztyn (Ordinance of the Council of Ministers of 18 October 2016 on the Adoption of the Flood Risk Management Plan for the Pregolya River Basin, 2016) (Figure 3.7).

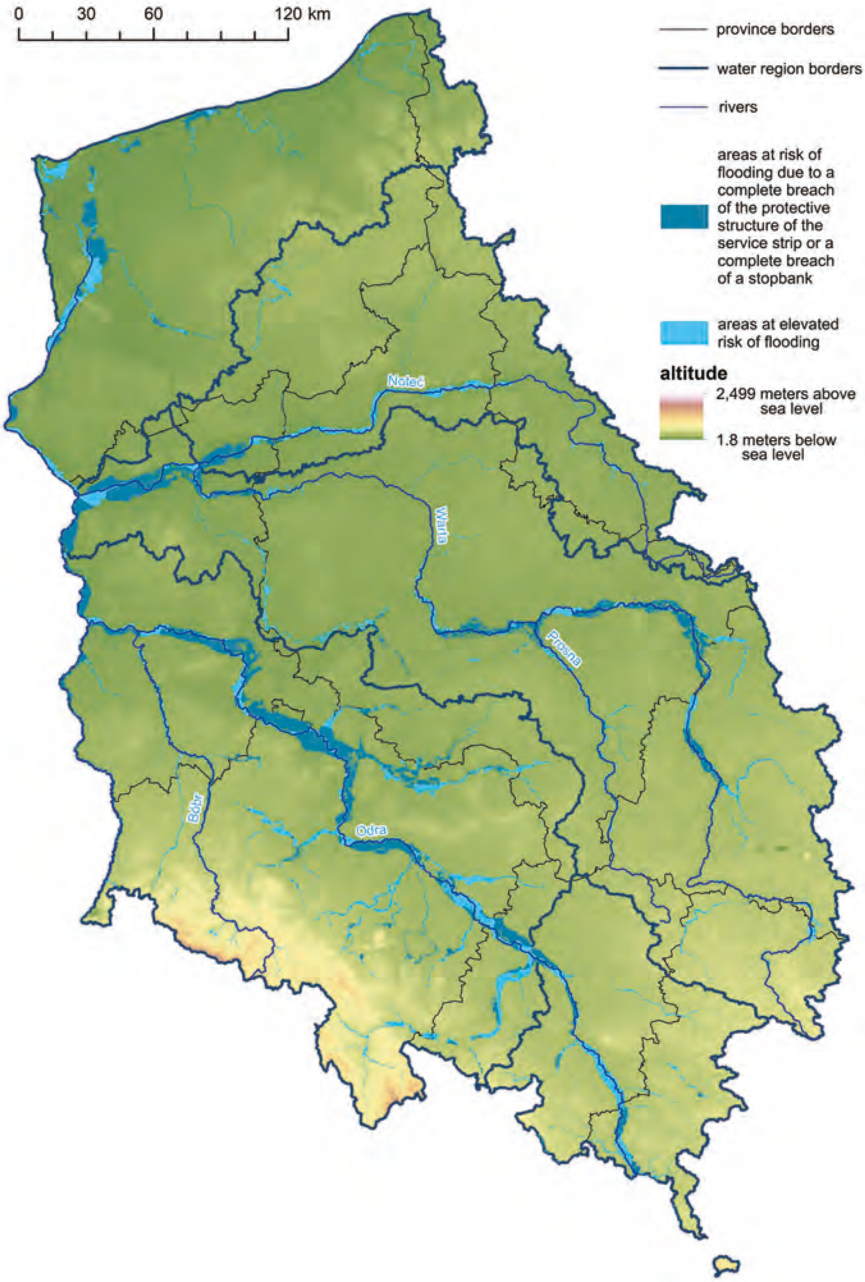

Figure 3.6. Flood hazard areas against the background of the topographical relief in the basin of the Oder in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Digital Terrain Model by Head Office of Land Surveying and Cartography (2019)

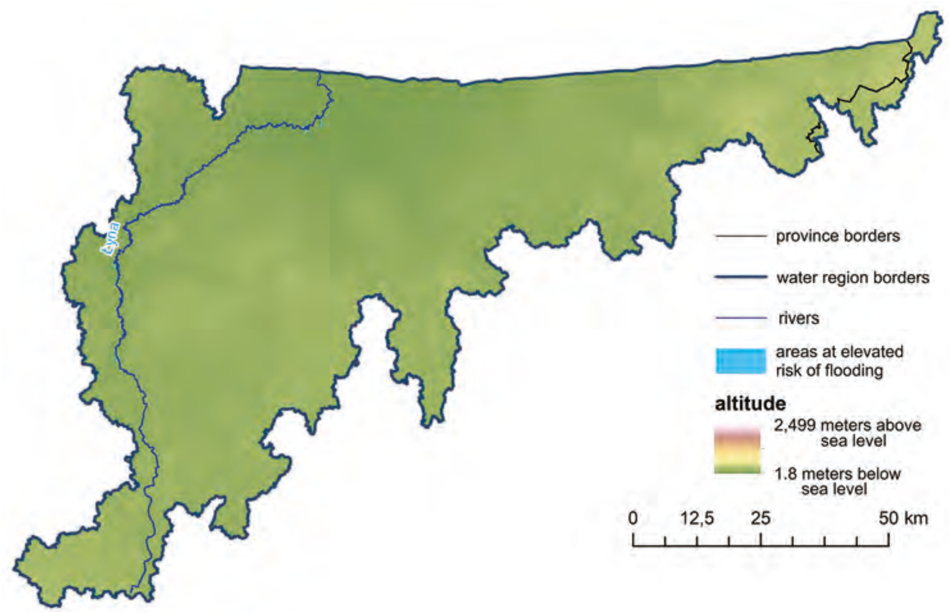

Figure 3.7. Flood hazard areas against the background of the topographical relief in the basin of the Pregolya in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Digital Terrain Model by Head Office of Land Surveying and Cartography (2019)

Importantly, within flood hazard areas located in the river valleys there are numerous protected sites that form part of the Natura 2000 network, as well as other forms of nature conservation, including landscape parks, nature reserves, areas of scenic value, nature-landscape sites, and natural monuments (Figure 3.8).

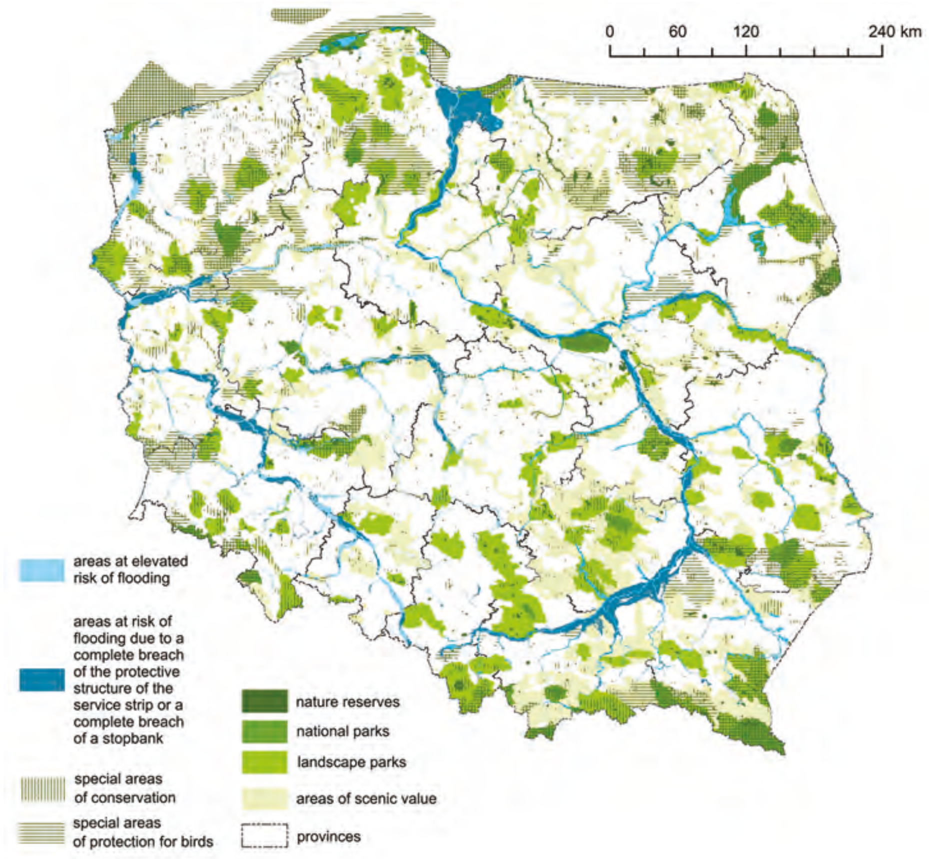

Figure 3.8. Forms of nature conservation against flood hazard areas in Poland in 2019
Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the General Directorate for Environmental Protection (2019)

3.2. Selected components of land use and population distribution in flood hazard areas

This subchapter presents data on land use in the flood hazard areas analysed for the different scenarios. The surface area and the magnitude of damage for the phenomenon (considering all forms of land use, including roads) is predicted and later used to demonstrate the extent to which areas important for transport would be affected. The second part of the subchapter contains the data on the number and distribution of the population in areas at risk, whose transport behaviour (reduced mobility, distinctive traits that impact evacuation, etc.) during a crisis situation may affect the road transport system.

3.2.1. Selected components of land use

In Poland, areas where there is a 10% probability of flooding are reported within the boundaries of 1,289 municipalities. The largest number of municipalities that have such areas are in Lower Silesian Province and Masovian Province (153 each). In Lower Silesia, the percentage of these areas per municipality does not exceed 25%, with the highest figure recorded for the municipality of Siechnice (24.3%). In Masovian Province, the percentage of flood hazard areas where there is a 10% probability of flooding is below 20% per municipality, with the highest value recorded for Nowy Dwór Mazowiecki (19.4%). The municipality with the largest percentage of areas at high risk of flooding in Poland is Goczałkowice-Zdrój (a rural municipality in the valley of the Upper Vistula), where the areas in question account for 65.7% of the total surface area. As for large cities (population over 100,000), this percentage is the highest in Włocławek and Toruń, where the percentages of areas at high risk of flooding amount to 19.6% and 14.9%, respectively. Warsaw ranks ninth, as the percentage of areas where there is a 10% probability of flooding equals 4.6% of the city's surface area (Figure 3.9).

Areas where there is a 1% probability of flooding are found within the boundaries of 1,302 municipalities in Poland. The highest number of municipalities where these areas are is in Masovian Province (155) and Lower Silesian Province (154). In Masovia, the percentage of areas where there is a 1% probability of flooding does not exceed 42%, with the highest value recorded for the municipality of Magnuszew (41.6%). As regards large cities and other areas at this probability of flooding, the percentage is highest in Włocławek (21.1%), followed by Toruń (16.2%). In Warsaw, which ranks tenth, at-risk areas constitute 4.9% of the city's surface area. These are sites in the city centre, so these are areas of high investment value and significance. The municipality with the highest percentage of areas where there is a medium probability of flooding is Goczałkowice-Zdrój (67.5%) (Figure 3.10).

Areas where there is a medium probability of coastal flooding have been identified in 58 municipalities, including 12 in Pomeranian Province, 22 in Warmian-Masurian Province, and 24 in West Pomeranian Province. The percentage per municipality does not exceed 40% (the highest figure is recorded for Jastarnia). As for large cities, such areas are found in only four locations across Poland: Szczecin (the clear leader, with 33.0% of the city area), followed by Gdańsk (9.0%), Elbląg (3.6%), and Gdynia (0.4%) (Figure 3.11).

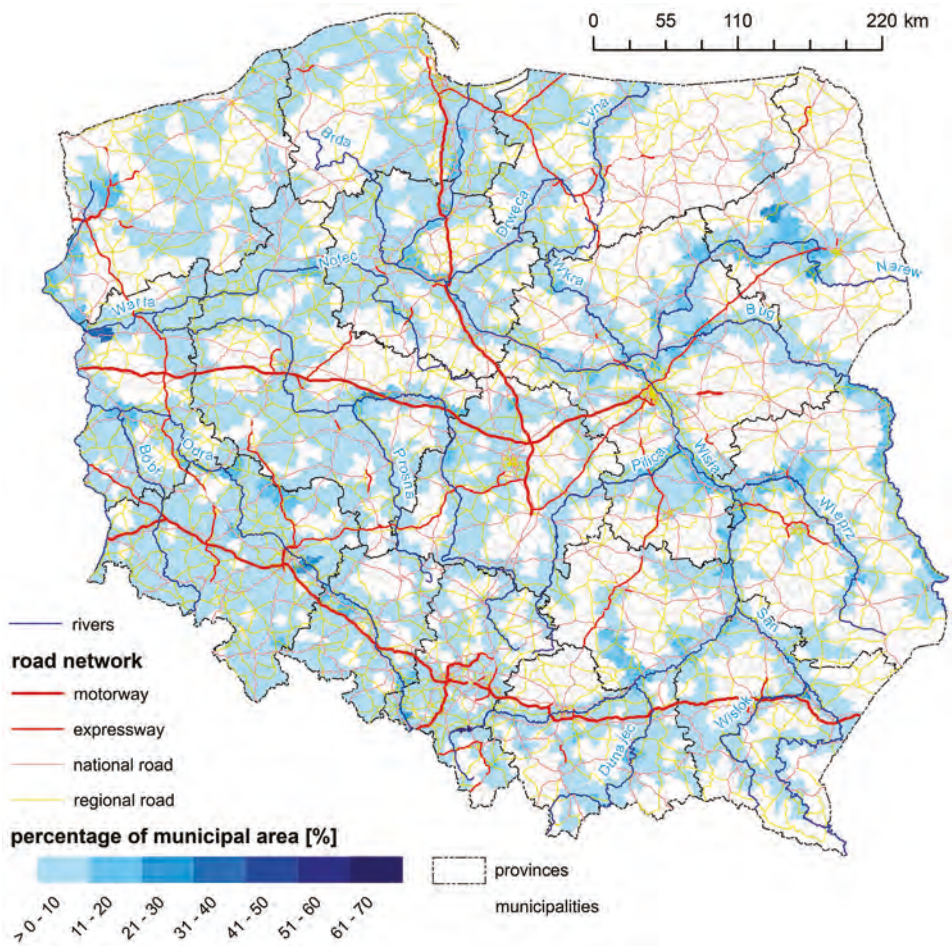

Figure 3.9. Percentage of total surface area identified as areas where there is a 10% probability of flooding in municipalities against the road network in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

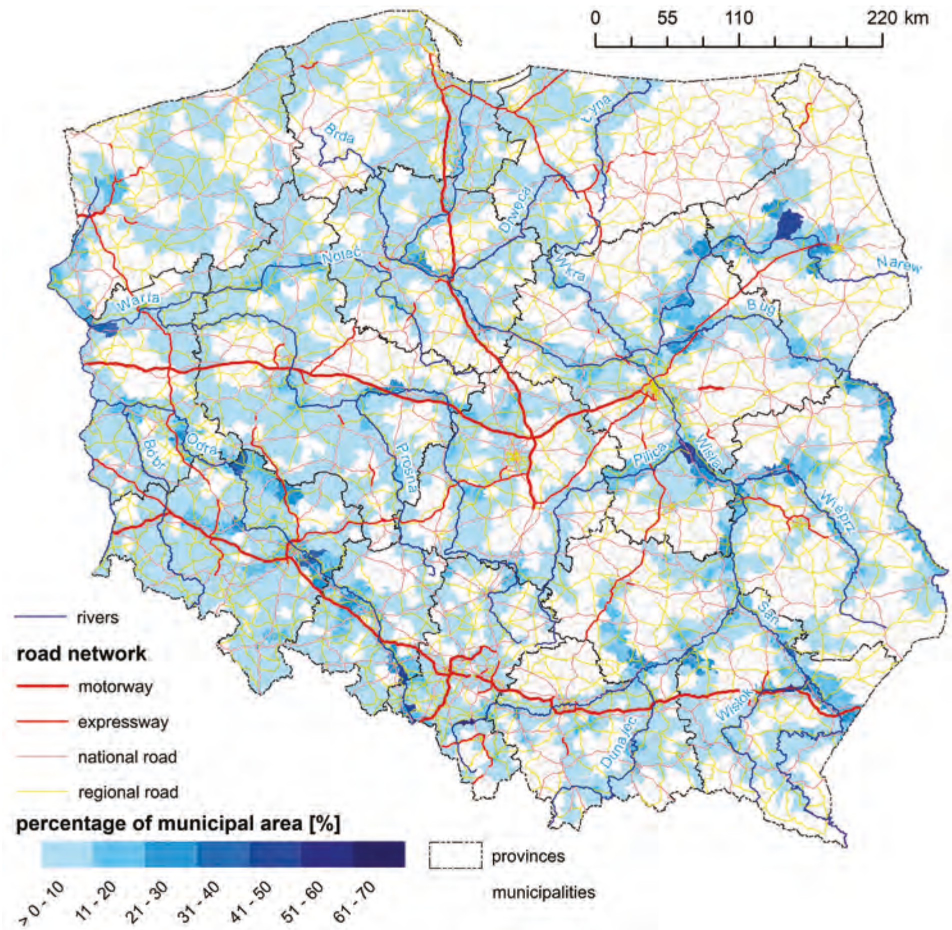

Figure 3.10. Percentage of total surface area identified as areas where there is a 1% probability of fluvial flooding in municipalities against the road network in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

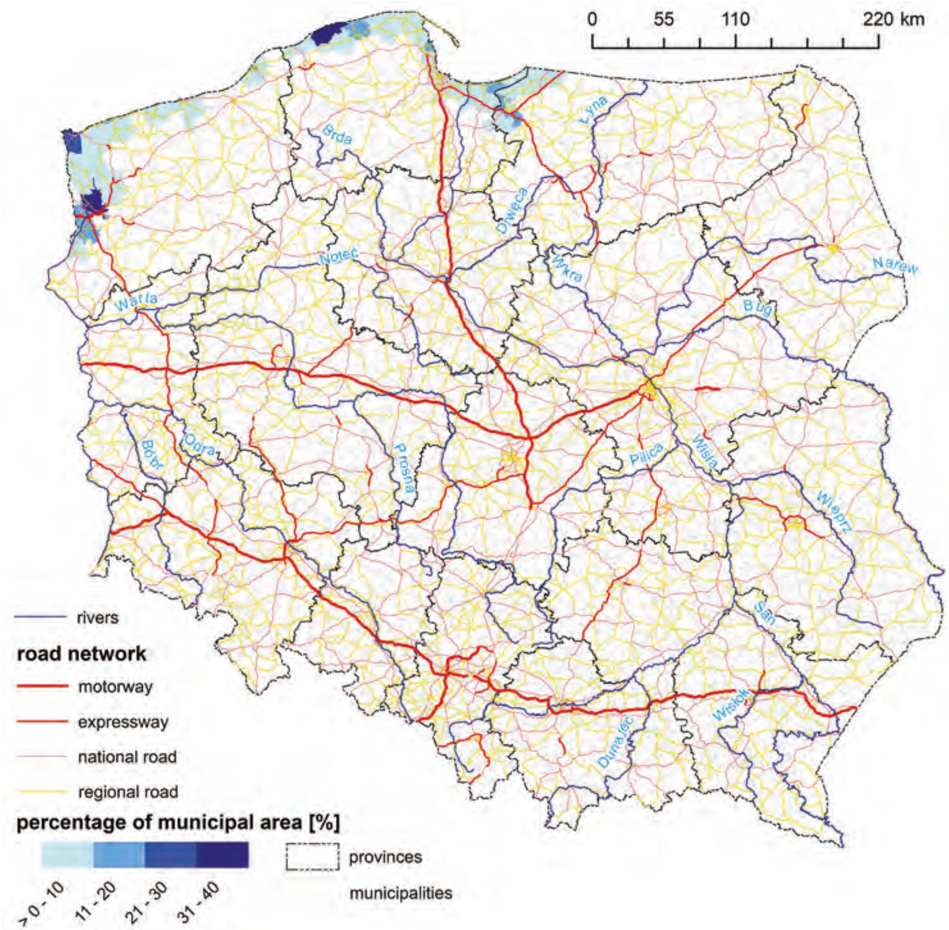

Figure 3.11. Percentage of total surface area identified as areas where there is a 1% probability of coastal flooding in municipalities against the road network in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

Areas at risk of flooding due to a complete breach of the protective structure of the service strip have been identified in 45 municipalities in Poland: 16 in Pomeranian Province, 15 in Warmian-Masurian Province, and 14 in West Pomeranian Province. In the municipality of Gronowo Elbląskie this percentage per total surface area is as high as 90.2%, followed by the municipality of Nowy Dwór Gdański (89.9%) (Figure 3.12).

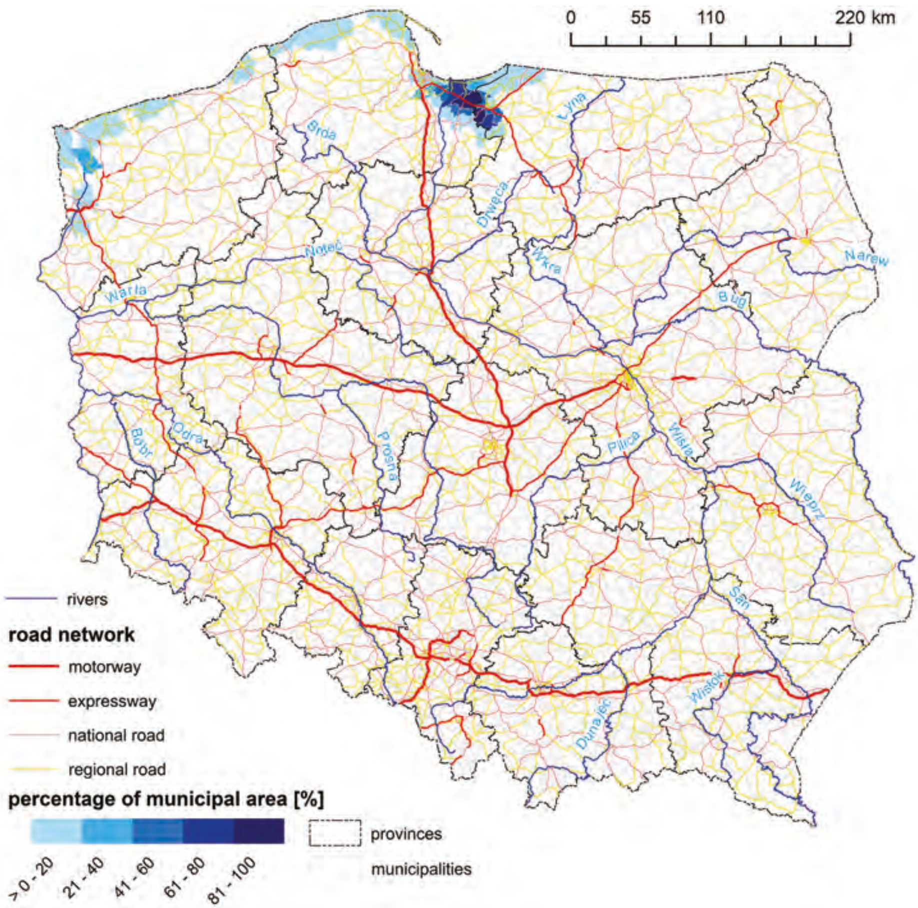

Figure 3.12. Percentage of total surface area identified as flood hazard areas in municipalities due to a complete breach of the protective structure of the service strip in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

Areas at risk of flooding due to a complete breach of a stopbank have been identified within 540 municipalities in Poland, of which the largest surface area is recorded in the basin of the Vistula. The highest number of municipalities with these areas is found in Lower Silesian Province (87). As for the highest percentage, it exceeds 90% in four municipalities, the highest being Nowy Dwór Gdański (96.30%) (Figure 3.13). Areas at risk of flooding due to a complete breach of a stopbank are also found in 24 large cities, the highest being in Kraków (21.8%), Gdańsk (16.0%), Gorzów Wielkopolski (15.6%), Warsaw (12.7%), and Wrocław (12.6%).

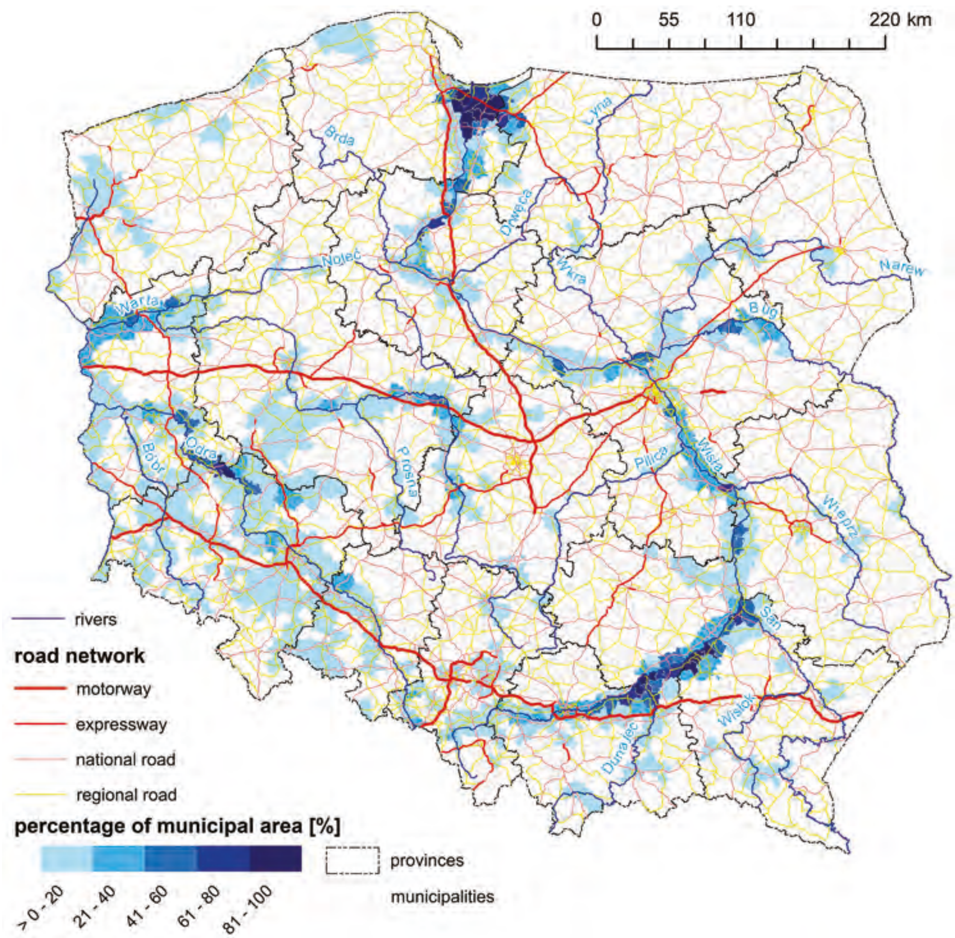

Figure 3.13. Percentage of total surface area identified as flood hazard areas in municipalities due to a complete breach of a stopbank in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

Besides transport areas (especially land carrying roads for vehicular traffic), it is also advisable to include, in further analyses, other areas where land use and development may affect the performance of road transport during and after a flood event and delay the transport network and other subsystems being restored to their pre-flood efficiency or to an acceptable level of equilibrium. This includes commercial and industrial zones. Obtaining data on what percentage of businesses would either be directly affected by the flood itself or "cut off" by flooding or road damage would make it possible to determine the changes in traffic generation and attraction potential of transport regions as early as the traffic modelling and simulation stage. This, however, would require a significantly more in-depth study, providing information on the employment scale in the affected businesses or the estimated number of potential customers/clients. This data would make it possible to determine what vehicle flows (taking into account modal split, etc.) would not appear on the road network in the event of a flood or would be diverted to other destination(s). Such an urban-scale analysis was undertaken by Siqueira-Gay et al. (2016), and the accuracy of their study indicates that this approach is possible for relatively small areas only (due to the volume of data and the need for it to be updated regularly). Despite this data not being available, the information on the pattern of land use in flood hazard areas under the scenarios applied here still provides a general insight into the magnitude at which such in-depth studies should be conducted.

Analysis of land use in flood hazard areas within all river basins reveals a number of regularities. Broadly speaking, there is a clear predominance of land-use types whose exclusion from use after inundation is not expected to affect the transport system to the extent indicted above. At the local (e.g., municipal) scale, the structure of land use may take a very different shape, and an in-depth analysis of traffic generation and attraction potential is possible and justified here. In areas at elevated risk of flooding the predominant type of land use is grassland and pastures, with the highest percentage reported in areas where there is a high risk of flooding (10%) – approximately 60% (highest in the Pregolya basin, lowest in the Oder basin). A slightly lower percentage (52%) is recorded in areas where there is a medium probability of flooding (1%), and in areas where there is a 1% probability of coastal flooding this value amounts to 59% (highest in the Pregolya basin, lowest in the Oder basin). As for areas where there is a 10% and a 1% probability of flooding, arable land ranks second as regards the surface area for each type of land use, and woodland ranks third, while this is reversed for areas where there is a 1% probability of coastal flooding. The basin of the Pregolya boasts the highest percentage of woodland within areas where there is a 10% and a 1% probability of flooding (when compared to the other basins). In the basin of the Oder, the percentage of woodland within areas where there is a medium probability of coastal flooding is 10 percentage points higher than in the basin of the Vistula.

As for the areas at risk of flooding due to a complete breach of the protective structure of the service strip, the dominant type of land use is arable land, occupying 65.30% of the total surface area of flood hazard areas (the percentage is considerably higher in the basin of the Oder), followed by grassland – 27.40% (the percentage is higher in the basin of the Vistula), and woodland – 3.90% (the percentage is considerably higher in the basin of the Oder).

As regards areas at risk of flooding due to a complete breach of a stopbank, the dominant type of land use is arable land, occupying 56% of their surface area (the percentage is noticeably higher in the basin of the Vistula), followed by grassland – 28.50% (the percentage is noticeably higher in the basin of the Oder), and woodland – 9.00% (the percentage is noticeably higher in the basin of the Oder) (Table 3.3).

Table 3.3. Land use in flood hazard areas by river basin in Poland in 2019 [%]

River basin	**Type of land use**	**Flood scenario**				
		10%	**1%**	**1%C**	**SSB**	**SB**
the Oder	1	0.28	1.00	0.91	0.66	1.73
	2	0.13	0.31	0.54	0.04	0.35
	3	0.14	0.35	0.35	0.17	0.55
	4	17.94	17.89	25.37	14.50	14.03
	5	0.31	0.53	1.57	1.86	0.66
	6	19.31	27.70	3.97	13.15	46.91
	7	58.67	49.51	61.97	68.85	35.06
	8	3.22	2.71	5.33	0.77	0.72
the Pregolya	1	0.13	0.29	–	–	–
	2	0.06	0.08	–	–	–
	3	0.02	0.04	–	–	–
	4	24.69	25.40	–	–	–
	5	0.77	0.93	–	–	–
	6	7.86	9.90	–	–	–
	7	64.44	61.16	–	–	–
	8	2.02	2.18	–	–	–
the Vistula	1	0.47	1.41	1.87	2.11	4.71
	2	0.16	0.27	1.65	0.30	0.67
	3	0.09	0.19	1.06	0.44	0.71
	4	13.73	14.07	15.58	2.34	6.53
	5	0.34	0.47	1.42	0.26	0.58
	6	16.70	24.26	15.39	73.08	60.95
	7	61.16	54.01	56.62	21.22	24.94
	8	7.35	5.33	6.40	0.24	0.91

1 – residential areas, 2 – industrial areas, 3 – transport areas, 4 – woodland, 5 – leisure and recreation areas, 6 – arable land, 7 – grassland and pastures, 8 – other areas (possible damage not calculated)

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019).

Following a flood with a 10% probability of occurrence, as many as 1,282 municipalities would suffer economic losses.[4] The highest losses would pertain to Sandomierz, since the Upper Vistula Valley between Oświęcim, Sandomierz and Zawichost is many kilometres wide. The floodplains of the Vistula are at their greatest where the river is joined by its large, right-hand, Carpathian tributaries: the Soła, the Skawa, the Raba, the Dunajec, the Wisłoka, and the San. Sadly, this has an impact on the land use in these areas, as developments are located mainly where the floodplain is widest (Borowska-Stefańska 2015b). The possible high economic losses mainly affect the provinces in southern Poland – Subcarpathia, Lesser Poland, Silesia, and Lower Silesia (Figure 3.14). High losses in the areas in question also apply to large cities – Warsaw, in particular – because of the vast residential and industrial areas within the floodplains (which justifies the said in-depth analysis of these areas).

Following a flood with a 1% probability of occurrence, as many as 1,286 municipalities in Poland would suffer economic losses. Here, both the total possible economic losses and those per hectare are significantly higher than in the scenario with a flood at high risk of occurrence. While the highest possible economic losses in the analysed areas pertain to the municipality of Lubomia (Silesian Province), the highest possible economic losses for areas at medium risk of flooding again primarily affect municipalities in southern Poland, Warsaw and its neighbouring municipalities (Figure 3.15).

Intensive land use and development in areas at elevated risk of flooding (10% and 1%) is mainly observed in cities and in places where the floodplains are wide and there are no stopbanks (Borowska-Stefańska 2015b). At the same time, the analysis of possible economic losses in areas at medium risk of coastal flooding shows that 52 municipalities would be affected. By far the worst case scenario is for Gdańsk, where possible economic losses would be over three times higher than in Szczecin (which ranks second in this regard) (Figure 3.16). This stems from the fact that the floodplains in Gdańsk are exceptionally wide where they form the estuarial section of the valley that forms the vast delta of the Vistula Fens near the Baltic Sea.

[4] Detailed methods for calculating these losses can be found in the Ordinance of the Minister of the Environment, the Minister of Transport, Construction and Maritime Economy, the Minister of Administration and Digitisation and the Minister of the Interior of 21 December 2012 on the Preparation of Flood Hazard Maps and Flood Risk Maps, Journal of Laws 2013, Item 104.

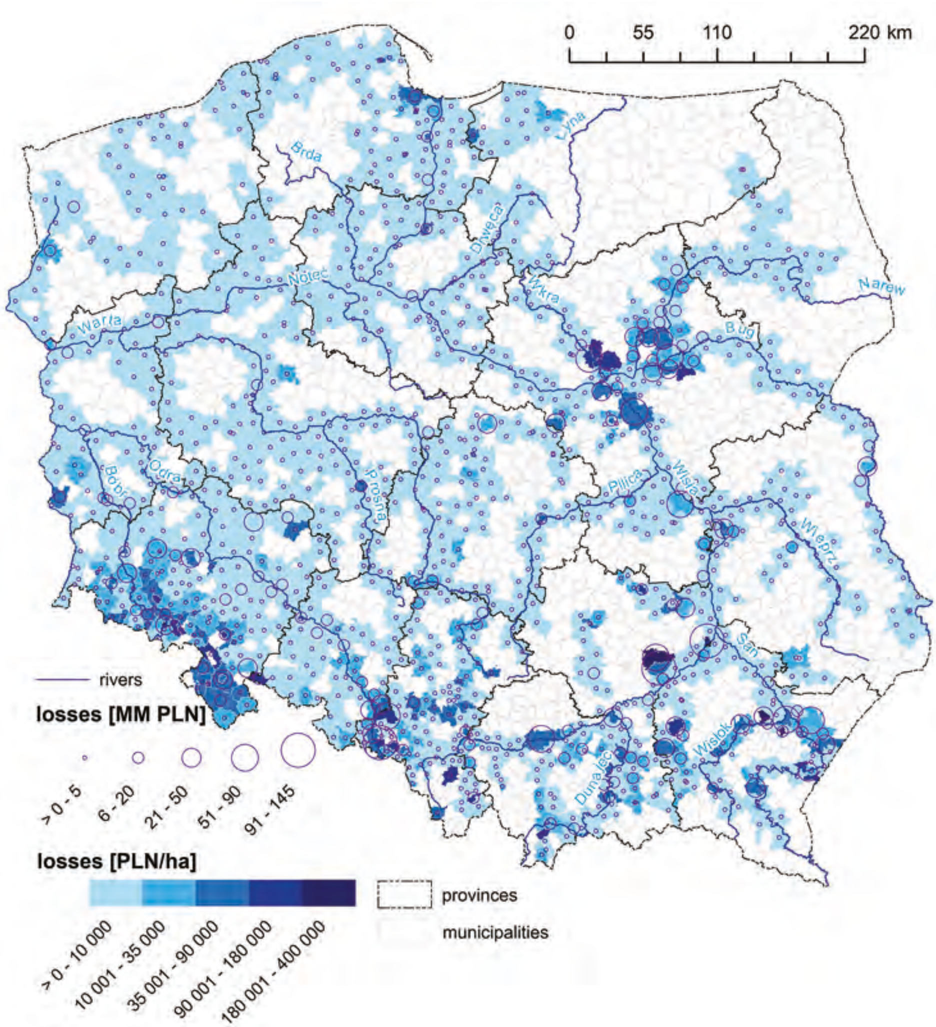

Figure 3.14. Economic losses per hectare of area at risk and total magnitude of possible economic losses due to the occurrence of a flood with a 10% probability in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

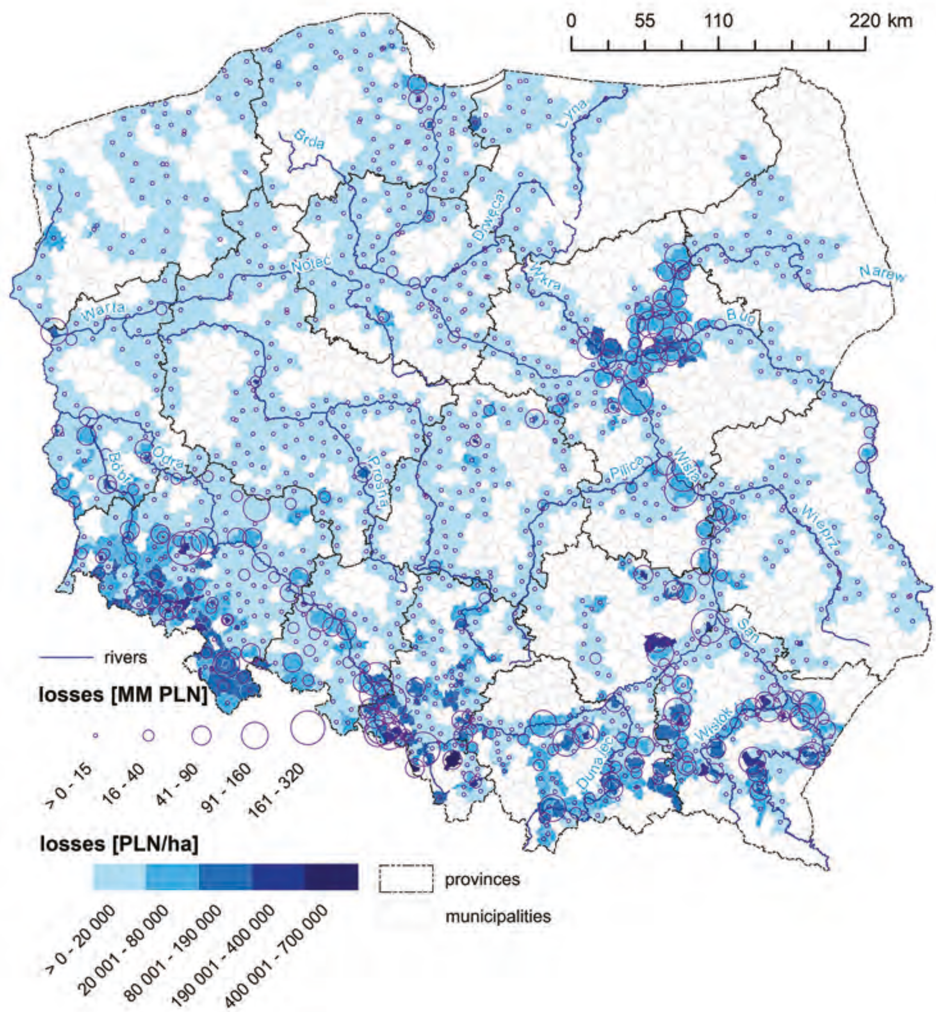

Figure 3.15. Economic losses per hectare of area at risk and total magnitude of possible economic losses due to the occurrence of a fluvial flood with a 1% probability in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

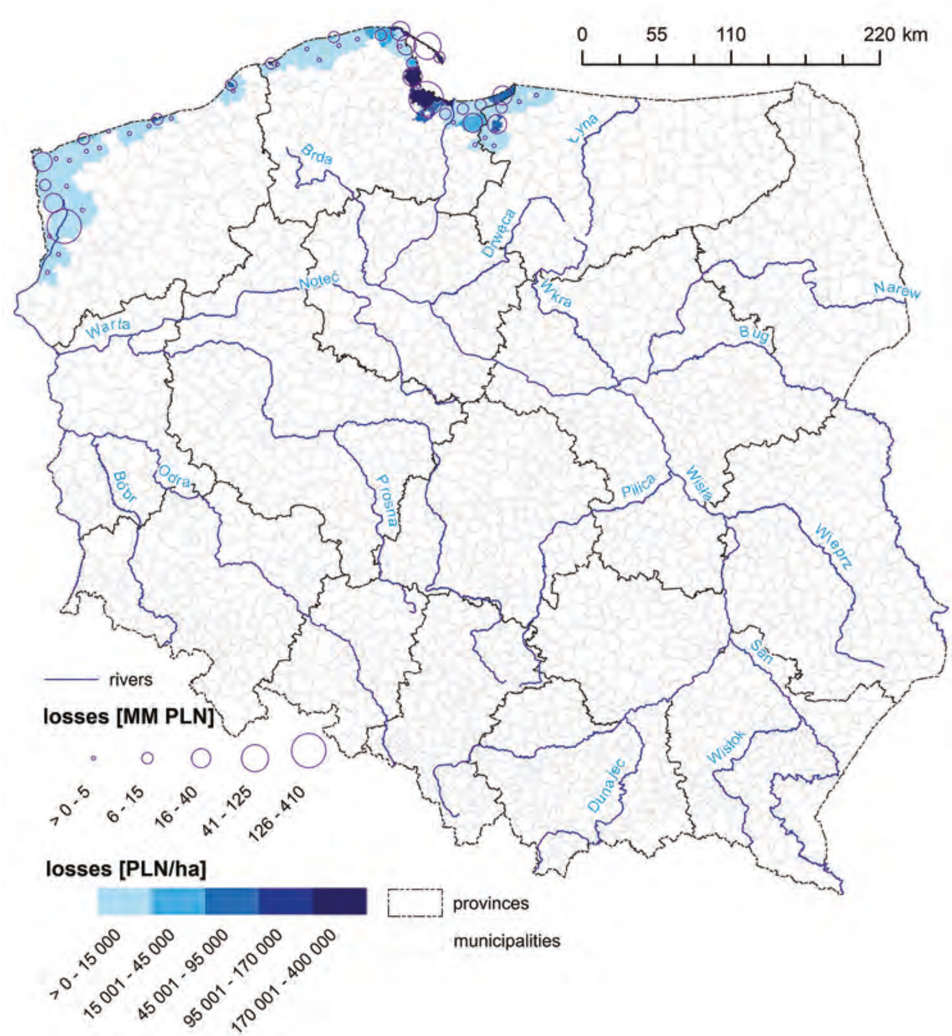

Figure 3.16. Economic losses per hectare of area at risk and total magnitude of possible economic losses due to the occurrence of a coastal flood with a 1% probability in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

In the event of a flood in areas at risk of flooding due to a complete breach of the protective structure of the service strip, possible economic losses would affect 44 municipalities, with the highest losses occurring in municipalities within the estuarine section of the Vistula (Figure 3.17).

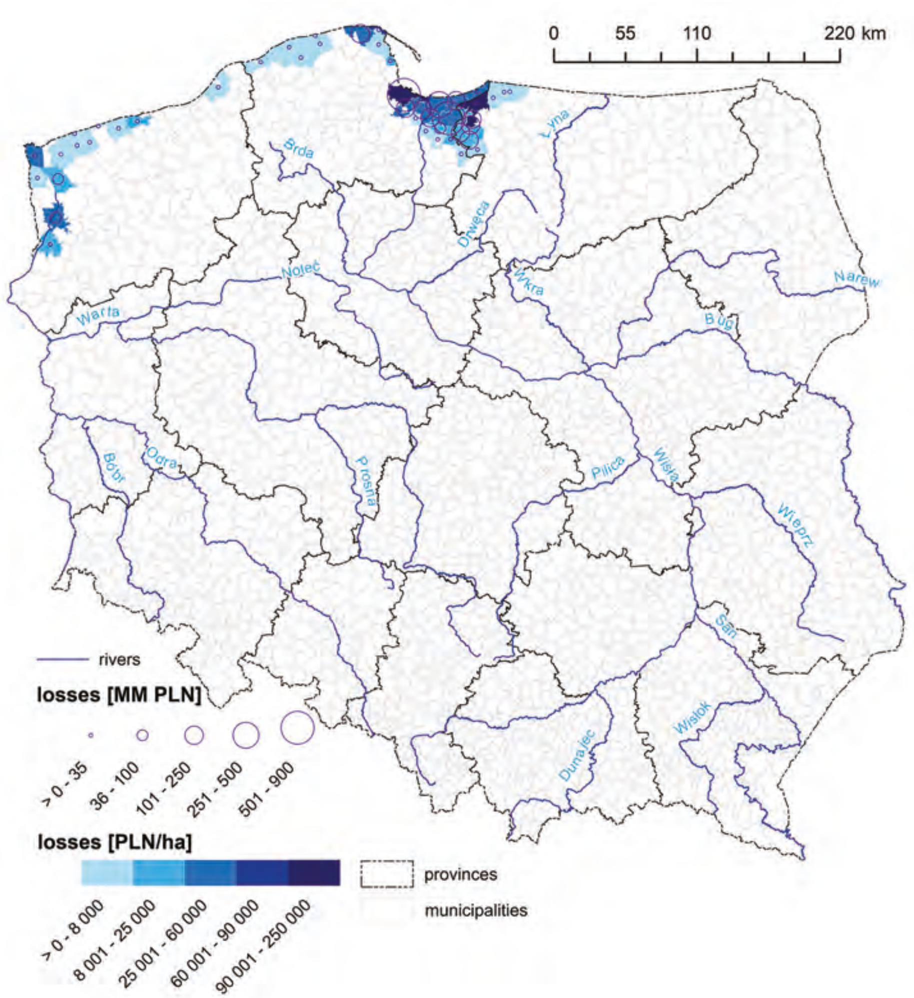

Figure 3.17. Economic losses per hectare of area at risk and total magnitude of possible economic losses following the occurrence of a flood due to a complete breach of the protective structure of the service strip in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

The analysis of possible economic losses in flood hazard areas due to a complete breach of a stopbank reveals that as many as 540 municipalities would be affected. By far the highest losses would apply to two large cities – Warsaw and Kraków. In Kraków, this stems from the fact that the Vistula valley is exceptionally broad there (up to 5 km in width). The valley floor is protected by stopbanks, allowing the areas behind them to be intensively developed, which makes the possible economic losses in Kraków high when combined with the natural conditions (tectonic and geomorphological properties of the valley). In Warsaw, the risk of high economic losses results from the fact that the sizeable, affected areas are located within the city centre. The analysis shows that the potential economic losses in the areas in question are mostly associated with the valley of the Vistula River (Figure 3.18).

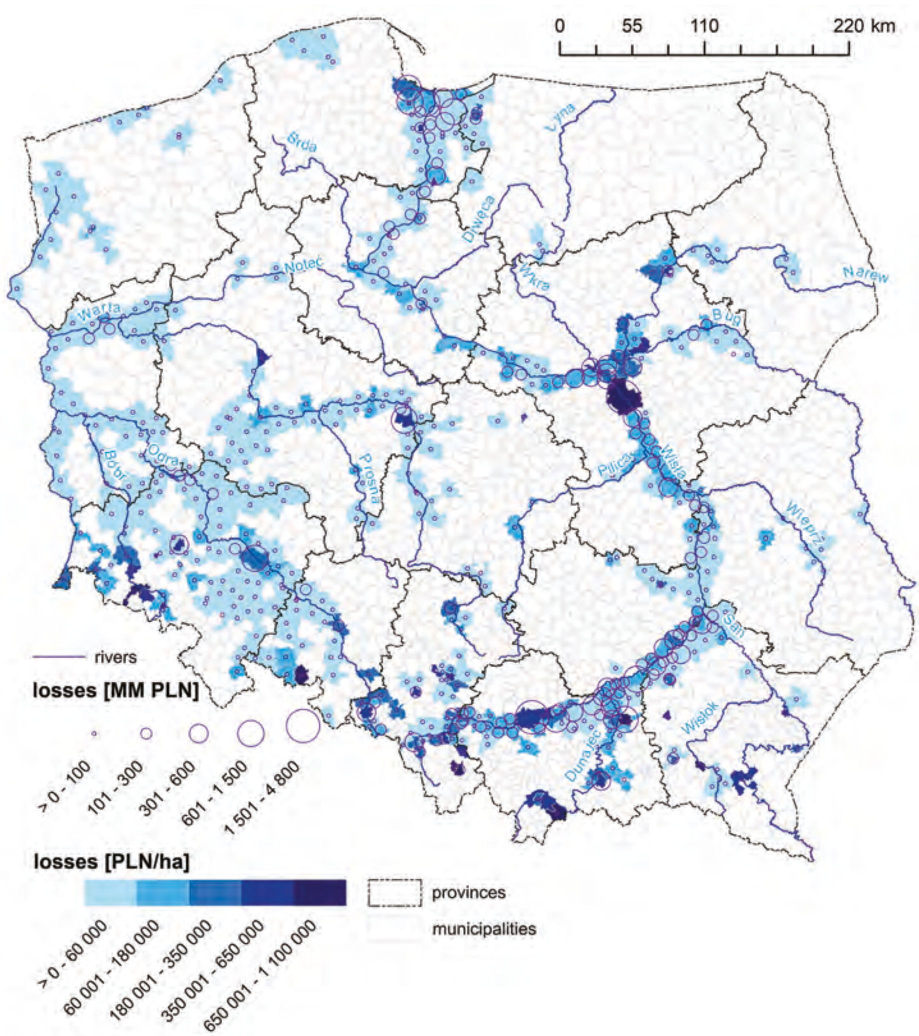

Figure 3.18. Economic losses per hectare of area at risk and total magnitude of possible economic losses following the occurrence of a flood due to a complete breach of a stopbank in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

The high intensity of land use behind the stopbanks is based on the assumption that the protective structures are infallible and also that these extensive areas are often located within city limits, which renders it impossible to ignore them in the plans for land use and development.

Floods with a 10% probability of occurrence are particularly dangerous for transport infrastructure within the water region of the Middle Oder, since almost one third of all such areas at risk in Poland are located in this region. This figure is even more unfavourable for floods with a medium probability of occurrence (reaching almost 40%). As for scenarios involving coastal flooding, the impact of the sea would be most destructive for transport infrastructure in the water region of the Lower Vistula. In contrast, over 25% of all transport infrastructure at risk of flooding due to a complete breach of a stopbank is found in the water region of the Upper Western Vistula (Table 3.4).

A flood with a 10% probability of occurrence would result in economic losses following damage to transport infrastructure in 810 municipalities. The highest possible losses would be suffered by Warsaw. The high possible economic losses resulting from damage to transport infrastructure would also apply to municipalities in Lower Silesia, whose total possible economic losses is also significant (Figure 3.19). The average percentage of possible losses due to damage to transport infrastructure against the total number of municipalities affected by the flood in this scenario amounts to 11.9% and varies considerably, as the standard deviation exceeds 19 percentage points. The highest average percentage applies to Kuyavian-Pomeranian Province (19.3%) where such losses would occur within 42 municipalities. This is also the region where the changeability of this parameter is clearly the highest (the standard deviation is as high as 24.8 percentage points). When taking into account only the number of municipalities where losses to transport infrastructure may occur, by far the most unfavourable situation is in Lower Silesia (119 municipalities).

Following a flood with a 1% probability of occurrence, as many as 906 municipalities would suffer economic losses due to damage to transport infrastructure. In this scenario, the possible economic losses are highest in the urban-rural municipality of Siechnice (Lower Silesian Province). A flood of this type would cause the greatest losses in transport infrastructure in municipalities located in Lower Silesian and Opole Provinces. Warsaw ranks tenth for the total losses to transport infrastructure (Figure 3.20). Compared to the scenario of a flood with a high probability of occurrence, there is a decrease in the average percentage of possible flood-related losses in transport infrastructure (down to 9.2%). The variability of results also decreases by ca. 5 percentage points. When taking into account the percentage of the surface area, the highest average value applies to Świętokrzyskie Province (14.1%). However, this figure was calculated from data for only 33 municipalities. Lower Silesia has the largest number of municipalities in this regard (125). Considering possible losses caused by flooding of transport infrastructure in absolute terms, Masovian Province appears to be in the most unfavourable situation.

Table 3.4. Land use in flood hazard areas in Poland by water region in 2019 [%]

Food scenario	Type of land use	Land use in flood hazard areas [ha]												
		the Vistula basin							the Oder basin					the Pregolya basin
		the Bug water region	the Lower Vistula water region	the Upper Eastern Vistula water region	the Upper Western Vistula water region	the Little Vistula water region	the Narew water region	the Middle Vistula water region	the Lower Oder and the coastal strip of West Pomerania water region	the Upper Oder water region	the Noteć water region	the Middle Oder water region	the Warta water region	the Łyna and the Węgorapa water region
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
10%	1	9.15	2.65	8.15	18.55	0.74	4.79	25.89	1.47	7.69	0.74	15.63	4.48	0.07
	2	1.14	2.79	22.65	21.41	0.44	0.44	14.54	0.83	17.04	0.20	16.01	2.41	0.09
	3	3.03	10.55	7.06	13.74	0.97	1.56	10.59	2.40	11.53	0.81	31.33	6.37	0.04
	4	9.29	5.89	4.65	6.02	0.36	8.55	16.59	5.79	1.90	2.19	28.49	9.91	0.35
	5	7.31	12.44	14.24	7.63	0.53	1.94	15.70	3.25	4.58	2.30	24.24	5.31	0.52
	6	7.25	9.50	14.62	6.16	0.56	2.07	14.39	1.54	9.38	0.79	21.78	11.87	0.10
	7	13.51	5.56	4.01	7.90	0.49	14.13	13.42	5.84	1.24	6.36	13.00	14.30	0.24
	8	5.06	5.09	6.38	19.99	1.03	4.84	33.60	1.96	1.80	3.58	4.68	11.91	0.08
1%	1	5.67	2.74	19.02	11.81	1.85	5.73	18.35	0.95	9.89	0.41	20.05	3.49	0.04
	2	1.00	2.97	21.78	14.89	1.86	0.88	10.05	0.97	14.23	0.89	25.98	4.44	0.05
	3	2.73	5.41	10.32	10.57	2.19	1.64	8.24	1.61	14.03	0.55	38.29	4.38	0.03
	4	8.92	5.18	4.55	4.86	0.54	11.10	15.68	4.31	2.81	2.04	30.96	8.77	0.30
	5	5.88	7.94	13.75	6.66	1.55	2.62	15.37	2.74	7.95	1.38	29.78	4.03	0.35
	6	5.93	6.03	19.54	4.81	0.79	2.86	13.65	1.04	9.82	1.06	25.57	8.81	0.07
	7	12.58	5.34	5.81	6.94	0.65	13.84	13.76	4.90	1.93	7.20	13.69	13.14	0.22
	8	4.98	4.66	6.40	18.51	1.63	5.71	30.28	1.98	2.73	5.79	6.30	10.93	0.10

Table 3.4 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1%C	1	–	65.11	–	–	–	–	–	34.89	–	–	–	–	–
	2	–	73.71	–	–	–	–	–	26.29	–	–	–	–	–
	3	–	73.61	–	–	–	–	–	26.39	–	–	–	–	–
	4	–	35.91	–	–	–	–	–	64.09	–	–	–	–	–
	5	–	45.24	–	–	–	–	–	54.76	–	–	–	–	–
	6	–	77.96	–	–	–	–	–	22.04	–	–	–	–	–
	7	–	45.46	–	–	–	–	–	54.54	–	–	–	–	–
	8	–	52.30	–	–	–	–	–	47.70	–	–	–	–	–
SSB	1	–	95.57	–	–	–	–	–	4.43	–	–	–	–	–
	2	–	97.98	–	–	–	–	–	2.02	–	–	–	–	–
	3	–	94.62	–	–	–	–	–	5.38	–	–	–	–	–
	4	–	52.00	–	–	–	–	–	48.00	–	–	–	–	–
	5	–	48.71	–	–	–	–	–	51.29	–	–	–	–	–
	6	–	97.39	–	–	–	–	–	2.61	–	–	–	–	–
	7	–	67.39	–	–	–	–	–	32.61	–	–	–	–	–
	8	–	68.02	–	–	–	–	–	31.98	–	–	–	–	–
SB	1	1.25	15.49	8.18	34.49	2.11	0.36	21.38	0.17	2.25	0.26	8.28	5.78	–
	2	0.56	14.47	5.11	38.93	3.50	0.10	15.29	0.07	4.17	0.06	7.71	10.03	–
	3	0.32	18.46	4.61	25.81	2.14	0.35	18.89	0.45	3.51	0.10	19.56	5.81	–
	4	3.92	7.16	4.62	15.16	0.88	0.21	14.11	4.14	0.77	0.75	39.35	8.94	–
	5	2.30	12.96	3.32	13.78	3.43	0.44	25.40	1.30	3.63	0.00	22.77	10.66	–
	6	1.00	31.43	5.25	19.69	0.59	0.06	12.58	0.84	1.76	0.53	16.17	10.11	–
	7	4.60	14.72	4.75	17.81	1.25	0.55	13.06	3.87	1.07	4.36	14.63	19.35	–
	8	4.74	6.78	3.72	19.18	9.66	0.16	25.44	0.76	2.85	0.87	9.83	16.00	–

1 – residential areas, 2 – industrial areas, 3 – transport areas, 4 – woodland, 5 – leisure and recreation areas, 6 – arable land, 7 – grassland and pastures, 8 – other areas (possible damage not calculated).

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019).

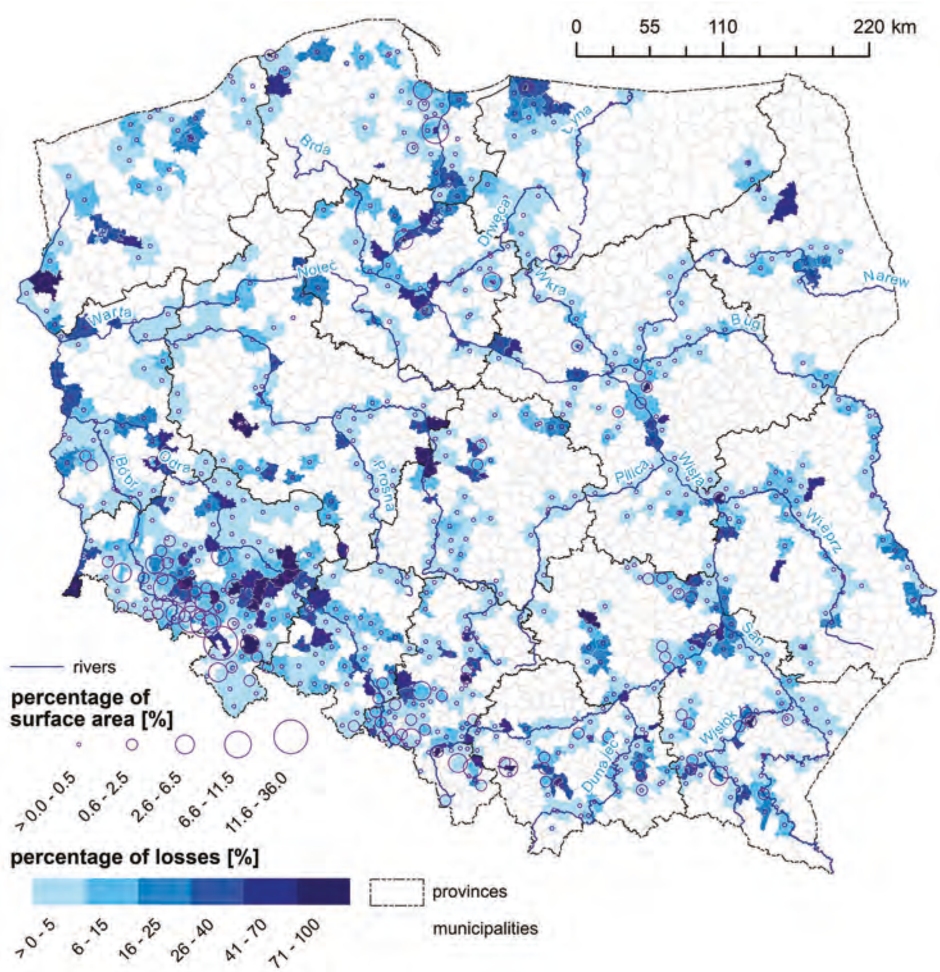

Figure 3.19. Percentage of the surface area and the possible losses due to flooding of transport infrastructure against the total surface area at risk and the total possible losses in municipalities due to a flood with a 10% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

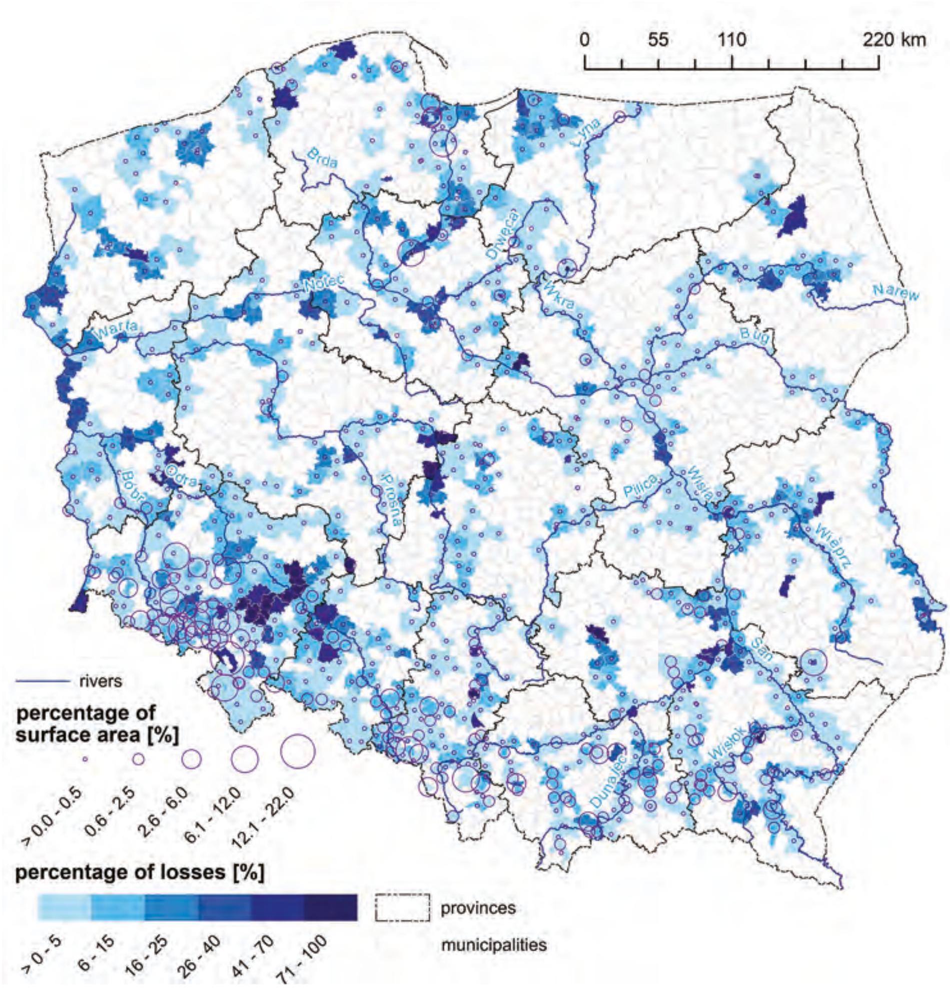

Figure 3.20. Percentage of surface area and possible losses due to flooding of transport infrastructure against the total surface area at risk and the total possible losses in municipalities due to a fluvial flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

The analysis of possible economic losses to transport infrastructure within areas at medium risk of coastal flooding reveals that they would affect 42 municipalities. Here, the worst case is definitely Gdańsk, where possible economic losses to transport infrastructure would be almost twice as high as in the urban-rural municipality of Jastarnia (which ranks second in this regard) (Figure 3.21).

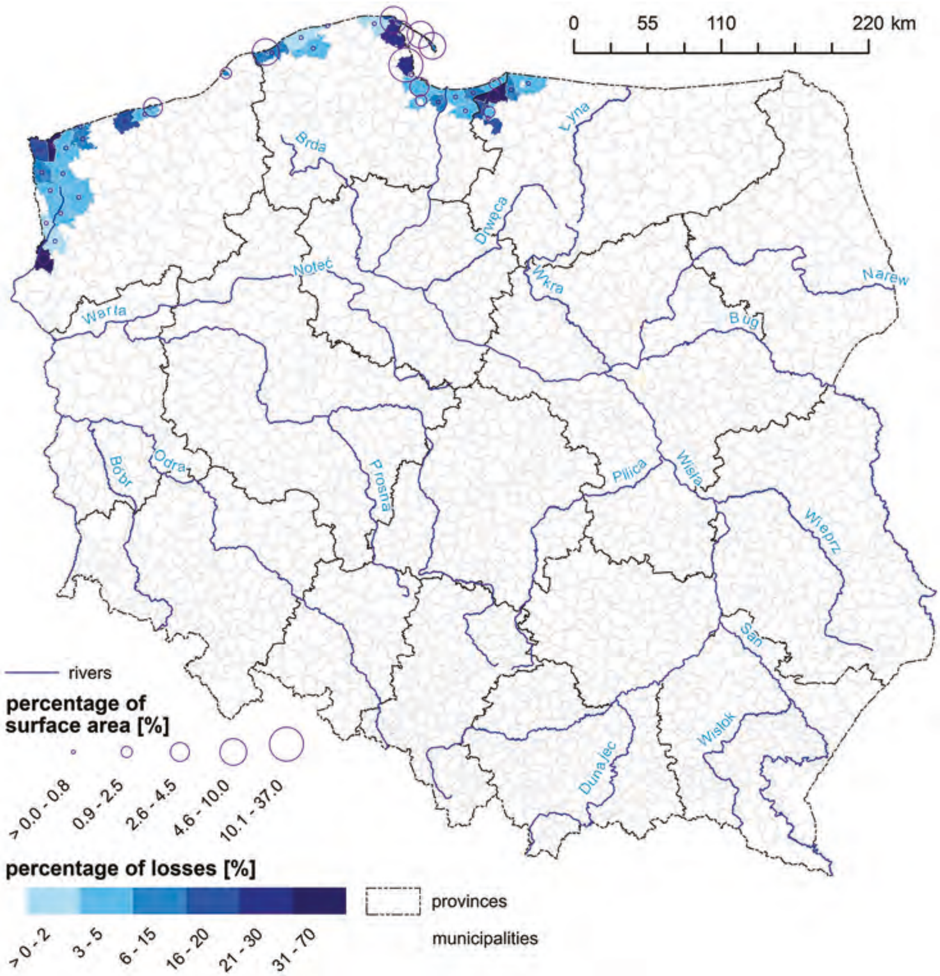

Figure 3.21. Percentage of surface area and possible losses due to flooding of transport infrastructure against the total surface area at risk and the total possible losses in municipalities due to a coastal flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

A flood event in the areas at risk of flooding due to a complete breach of the protective structure of the service strip would cause possible economic losses to transport infrastructure of 29 municipalities. The highest losses would be primarily recorded in municipalities located in the estuarian section of the Vistula (the first eight municipalities by total economic losses to transport infrastructure) (Figure 3.22).

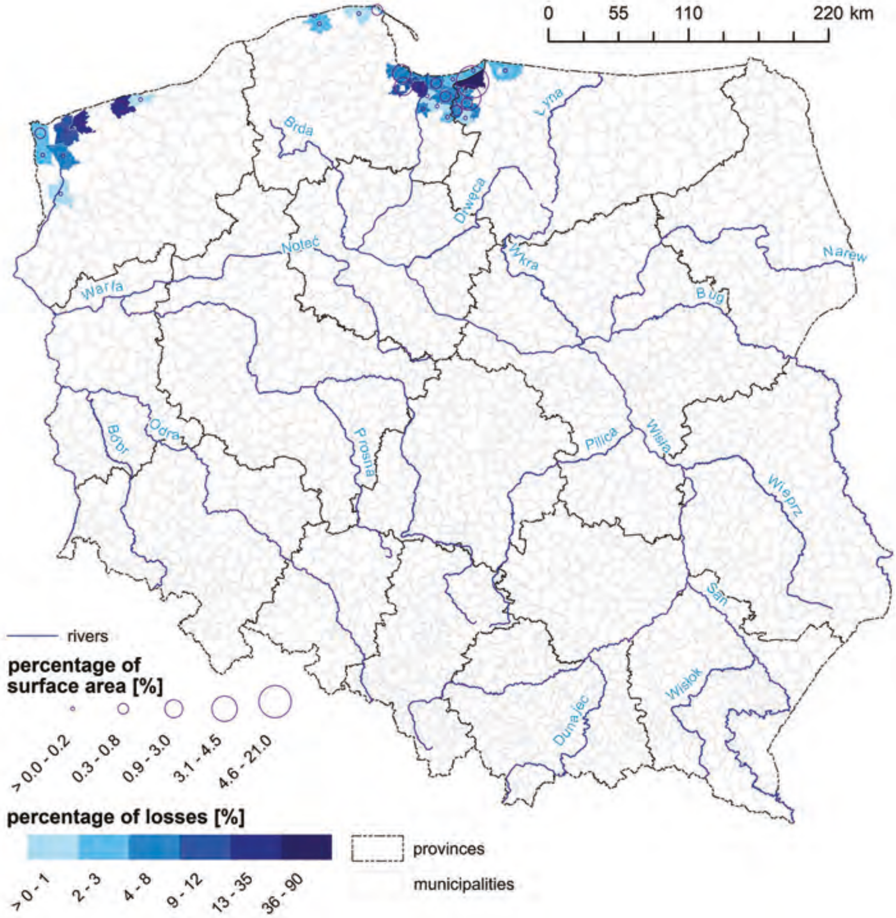

Figure 3.22. Percentage of surface area and possible losses due to flooding of transport infrastructure against the total surface area at risk and the total possible losses in municipalities following a flood due to a complete breach of the protective structure of the service strip in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

The analysis of possible economic losses to transport infrastructure within areas at risk of flooding following a complete breach of a stopbank reveals that they would affect 404 municipalities. By far the highest losses from damage to transport infrastructure (in the scenario where a stopbank is completely breached) would affect two large cities – Warsaw and Kraków, which is also true for total losses (Figure 3.23). The average percentage of possible losses for all municipalities in this scenario is 8.52% and, as in the previously analysed variants, it is characterised by a distinct variability (the standard deviation is 16.82 percentage points). The regional scale of the study reveals that this average increases significantly (it amounts to 17.04%), and, among all Polish provinces, it is clearly the highest for Lower Silesian Province, in which the number of municipalities where transport infrastructure may be flooded is also the largest (59). This number, however, is accompanied by the highest degree of variability in the percentage of total possible losses. In absolute terms, the highest possible losses due to flooding of transport infrastructure would occur in Masovian Province.

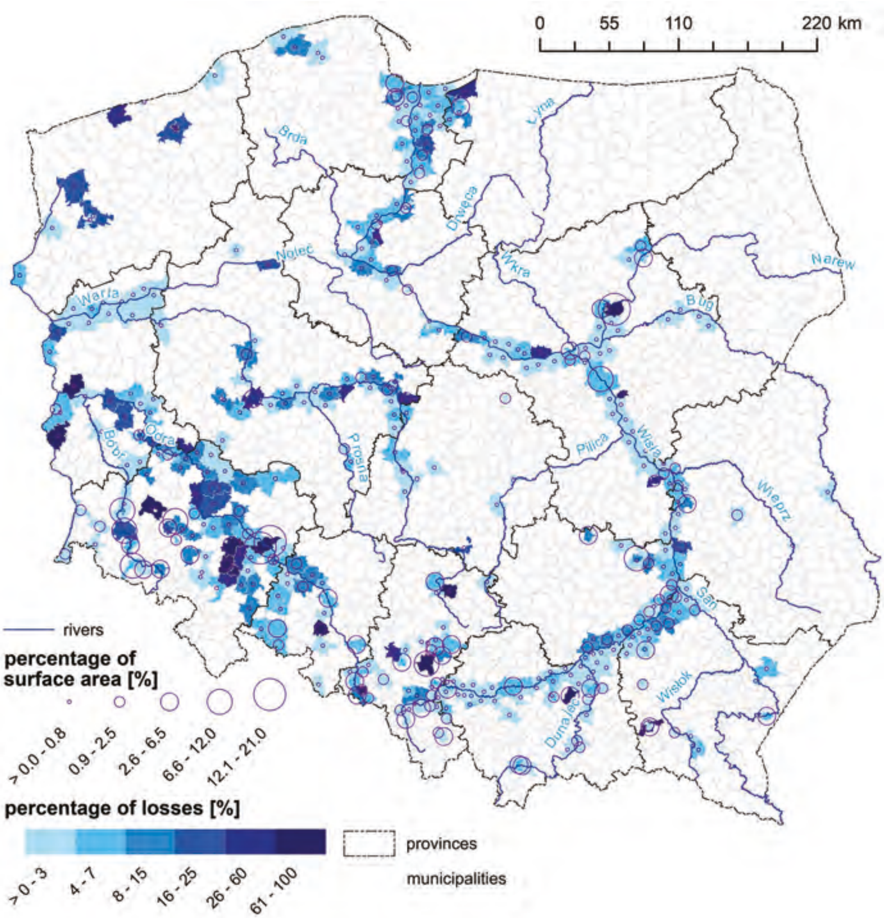

Figure 3.23. Percentage of surface area and possible losses due to flooding of transport infrastructure against the total surface area at risk and the total possible losses in municipalities following a flood due to a complete breach of a stopbank in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

The highest percentage of losses to transport infrastructure within the areas at elevated risk of flooding applies to the water region of the Middle Oder (for both areas where there is a high and a medium probability of flooding). As regards areas where there is a 1% probability of coastal flooding and areas at risk of flooding due to a complete breach of the protective structure of the service strip, the highest percentage of losses to transport infrastructure applies to the water region of the Lower Vistula. However, analysis of the percentage of possible economic losses to transport infrastructure (against the total losses for this type of land use) within the areas at risk of flooding due to a complete breach of a stopbank reveals that it is highest for the water region of the Upper Western Vistula (Table 3.5).

Data from the Database of Topographic Objects on land carrying roads for vehicular traffic[5] was incorporated to analyse types of land use and development within flood hazard areas in more detail. The inclusion of this data revealed that in the event of a flood with a 10% probability of occurrence 717 municipalities in Poland would suffer economic losses due to inundation of land carrying roads for vehicular traffic.[6] As shown in Figure 3.24, the percentage of losses to road infrastructure for vehicular traffic against the total losses to transport infrastructure is high and applies to most municipalities in Poland where there are areas at high probability of flooding. In the analysed scenario, the average percentage of possible losses (against the total transport infrastructure at risk of flooding) for all the municipalities where land carrying roads for vehicular traffic at risk of flooding was identified amounts to 68.14%, and – as confirmed by Figure 3.24 – it varies significantly, since the standard deviation is up to 36.37 percentage points.

[5] Carriageways, shoulders and facilities designed to be used by road traffic regardless of traffic flow obstructions, including roads where only pedestrian traffic is allowed. Areas where no other elements of land cover can be distinguished (Definition of Databases of Topographical and General Geographical Objects and Technical Standards for the Production of Maps. Annex to the Ordinance of the Minister of Internal Affairs and Administration of 17 November 2011 on the Database of Topographic Objects and the Database of General Geographical Objects, and Standard Cartographic Works, Vol. 1).

[6] Importantly, the rate used to calculate the losses due to flooding of land carrying roads for vehicular traffic was determined taking into account the economic value of all types of transport infrastructure (including paved internal airport roads, trackage, etc.) on the basis of the Ordinance of the Minister of the Environment, the Minister of Transport, Construction and Maritime Economy, the Minister of Administration and Digitisation, and the Minister of Internal Affairs of 21 December 2012 on the Preparation of Flood Hazard Maps and Flood Risk Maps (Journal of Laws 2013, Item 104).

Table 3.5. The magnitude of possible losses due to flooding of transport infrastructure by water region and flood scenario in Poland in 2019 [%]*

Flood scenario	The magnitude of possible losses due to flooding of transport areas [%]												
	the Vistula basin							the Oder basin					the Pregolya basin
	the Bug water region	the Lower Vistula water region	the Upper Eastern Vistula water region	the Upper Western Vistula water region	the Little Vistula water region	the Narew water region	the Middle Vistula water region	the Lower Oder and the coastal strip of West Pomerania water region	the Upper Oder water region	the Noteć water region	the Middle Oder water region	the Warta water region	the Łyna and the Węgorapa water region
10%	2.90	11.56	7.47	14.18	0.99	1.63	11.24	2.22	11.40	0.66	29.44	6.29	0.04
1%	2.66	5.32	10.48	10.95	2.06	1.51	8.36	1.49	14.89	0.49	37.55	4.22	0.03
1%C	–	74.77	–	–	–	–	–	25.23	–	–	–	–	–
SSB	–	95.48	–	–	–	–	–	4.52	–	–	–	–	–
SB	0.30	20.16	4.09	26.30	1.97	0.33	18.41	0.41	3.68	0.08	18.75	5.51	–

* The differences compared to Table 3.4 stem from the application of varying rates of calculating economic losses, which – for transport infrastructure – depend on the depth of the floodwater

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019).

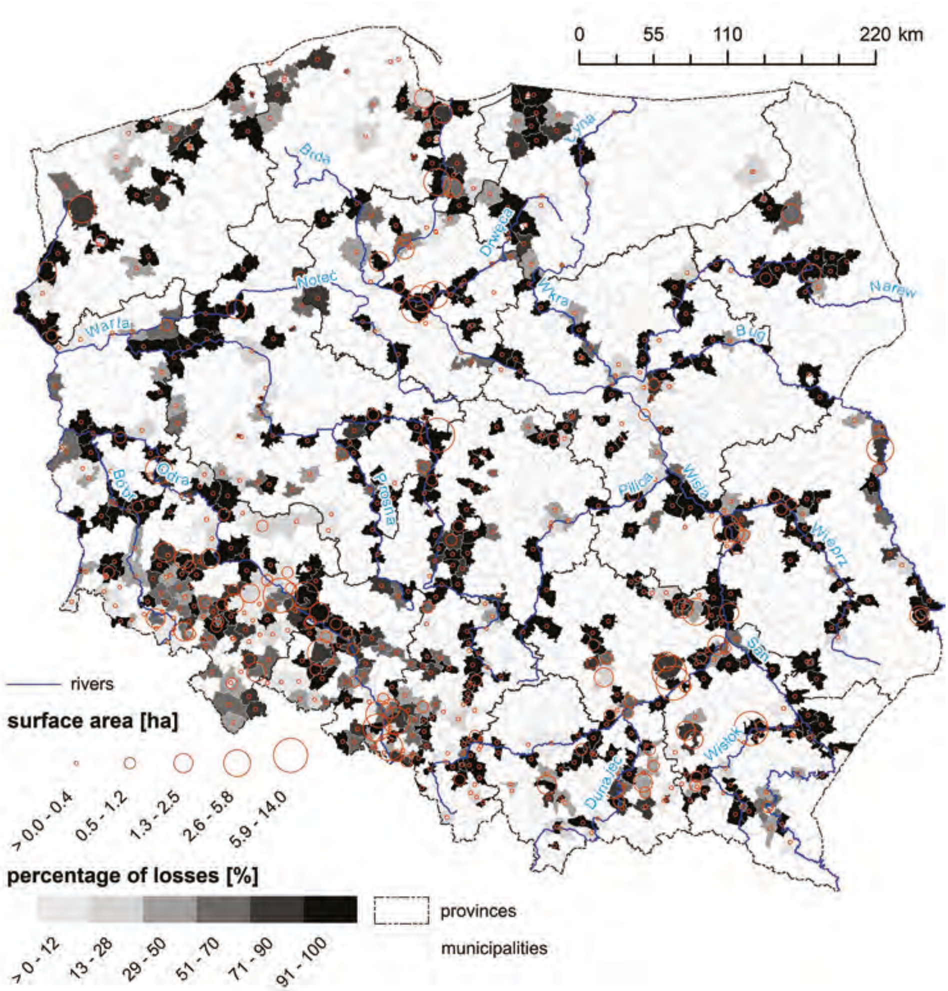

Figure 3.24. Surface area and percentage of possible losses due to flooding of land carrying roads for vehicular traffic against the total transport infrastructure at risk in the event of a flood with a 10% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

In the event of a flood with a 1% probability of occurrence, the number of municipalities that would incur economic losses due to inundation of land carrying roads for vehicular traffic would increase to 820. In both this variant and in the scenario of a flood with a high probability of occurrence, the possible economic losses concerning this type of land use (in total) would be highest for municipalities in south-western Poland (particularly in Lower Silesia, e.g., in the city of Legnica) (Figure 3.25). The average percentage and variability of the possible losses due to flooding of land carrying roads against the total possible transport losses in the municipalities would remain virtually unchanged compared to the scenario of a flood with a high probability of occurrence.

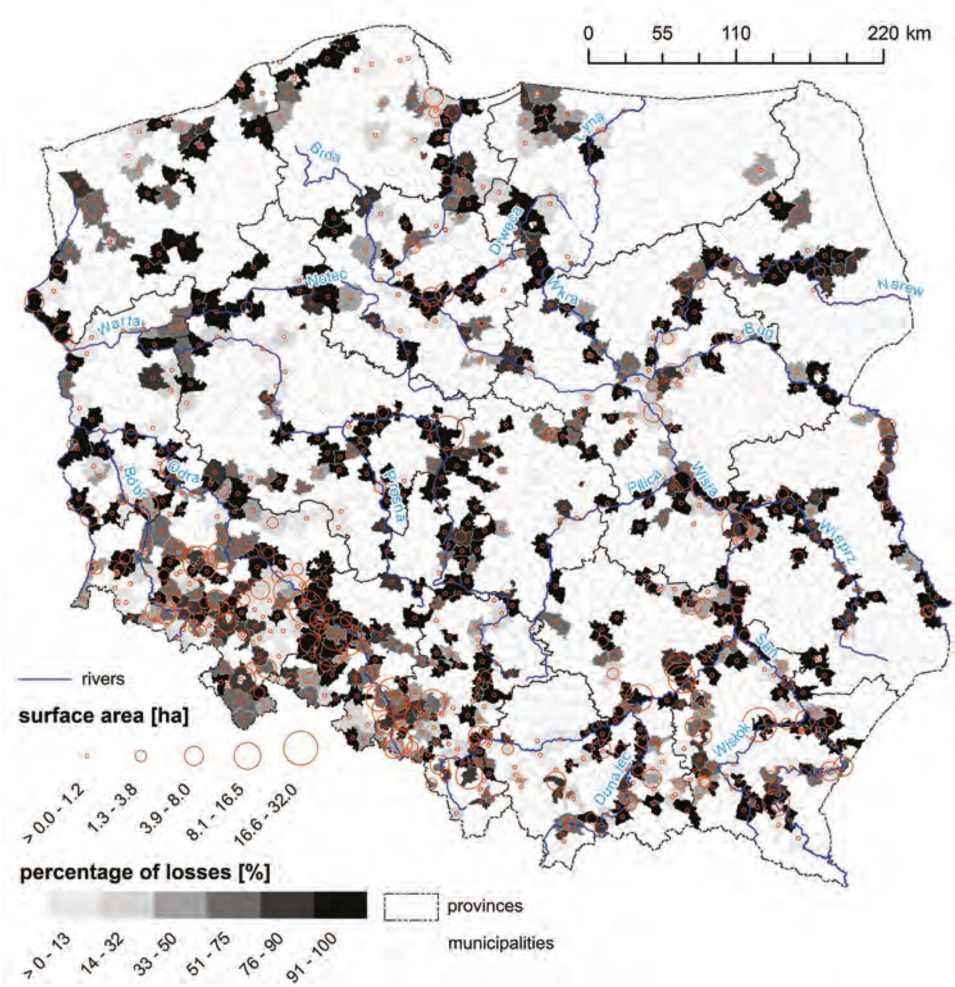

Figure 3.25. Surface area and percentage of possible losses due to flooding of land carrying roads for vehicular traffic against the total transport areas at risk in the event of a fluvial flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard map and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

The analysis of possible economic losses in land carrying roads for vehicular traffic within areas where there is a medium probability of coastal flooding reveals that 30 municipalities would be affected. The highest total volume of losses in question applies to Gdańsk, although this is not noticeable in relative terms (Figure 3.26).

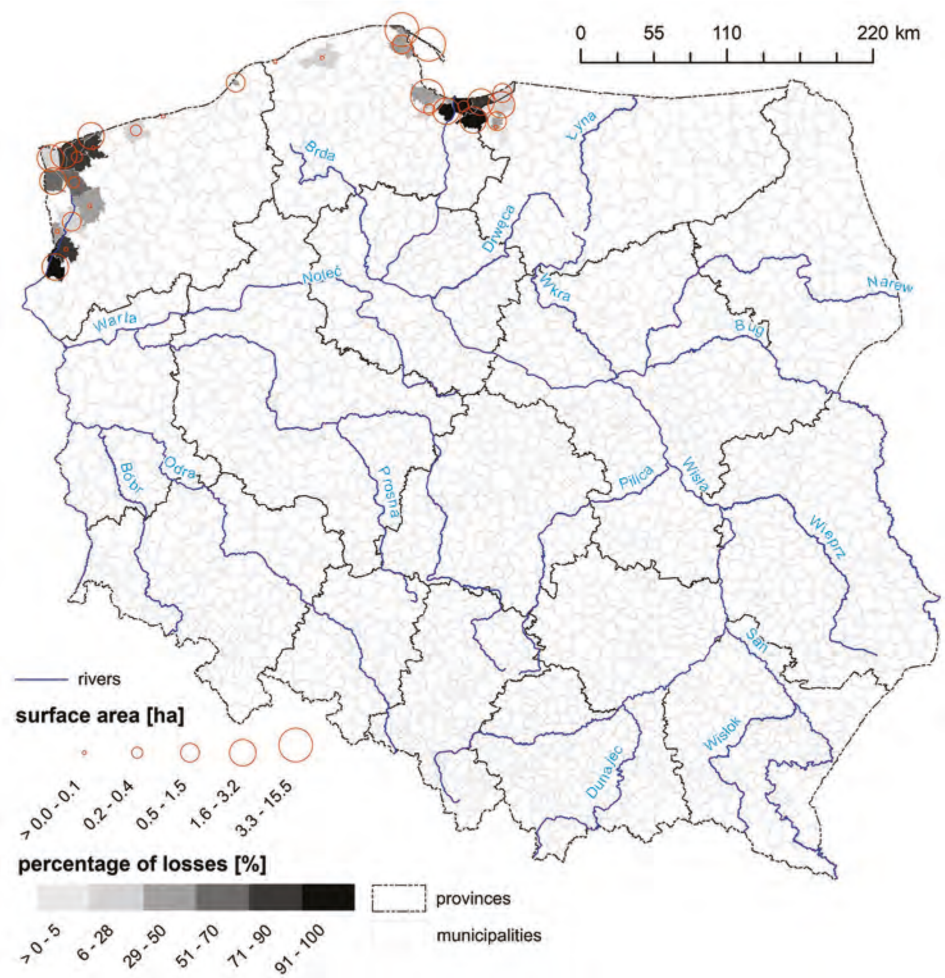

Figure 3.26. Surface area and percentage of possible losses due to flooding of land carrying roads for vehicular traffic against the total transport areas at risk in the event of a coastal flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

Following a flood event in areas at risk of flooding due to a complete breach of the protective structure of the service strip, potential economic losses in land carrying roads for vehicular traffic would be observed in 23 municipalities. As with the scenario discussed above, the highest losses in absolute terms would be incurred by municipalities located in the estuarine section of the Vistula (Figure 3.27).

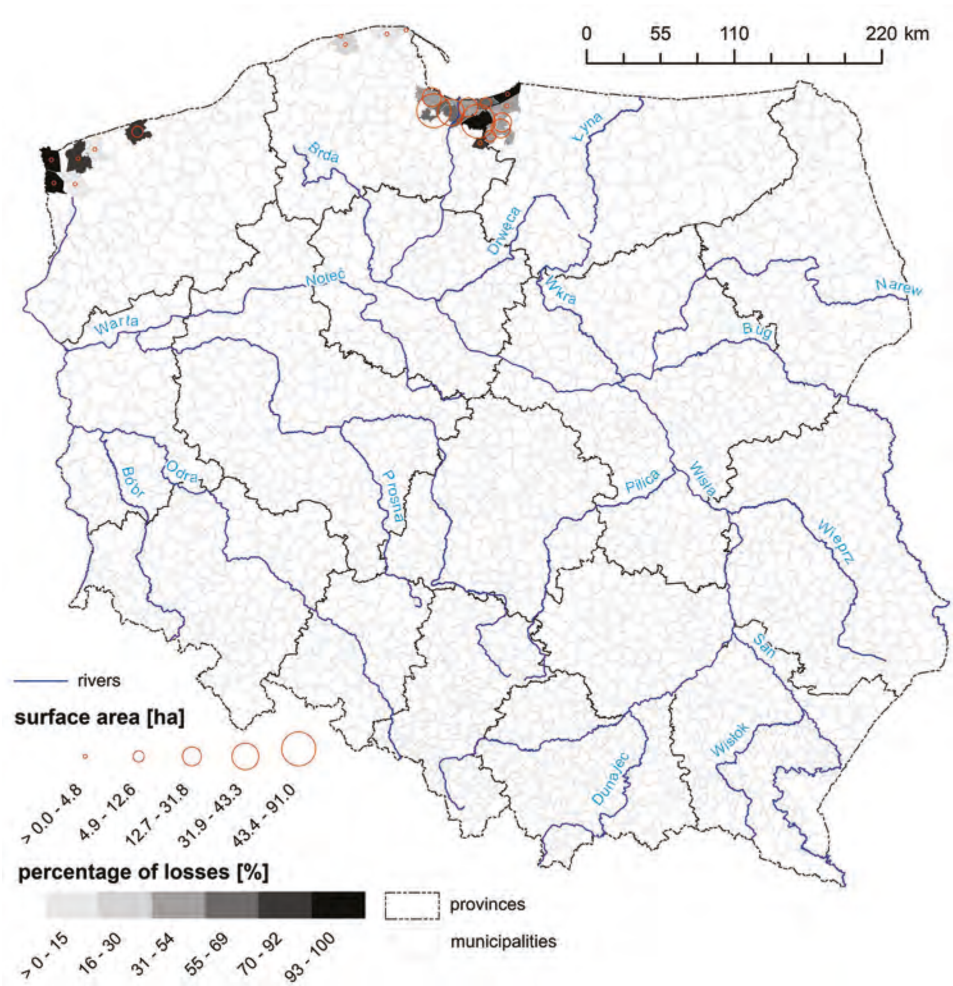

Figure 3.27. Surface area and percentage of possible losses due to flooding of land carrying roads for vehicular traffic against the total transport areas at risk in the event of a flood due to a complete breach of the protective structure of the service strip in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

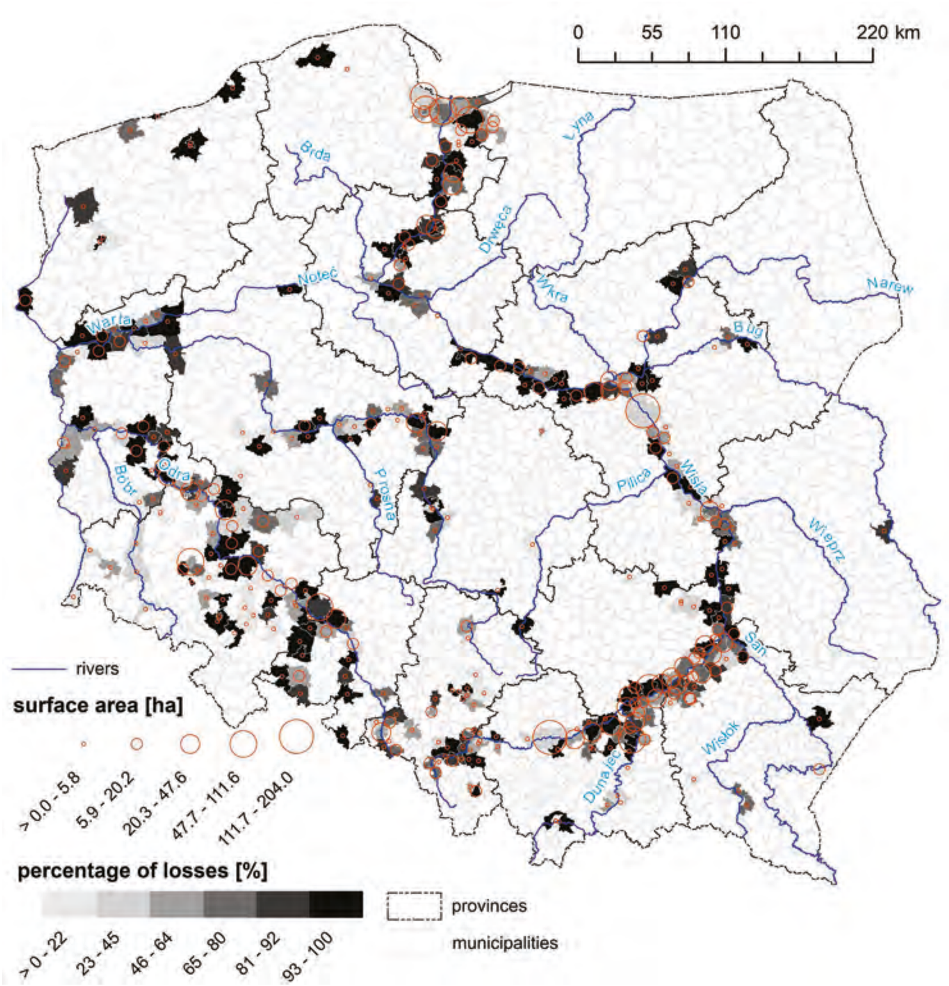

Figure 3.28. Surface area and percentage of possible losses due to flooding of land carrying roads for vehicular traffic against the total transport areas at risk in the event of a flood due to a complete breach of a stopbank in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

A complete breach of stopbanks could contribute to economic losses in the land carrying roads for vehicular traffic in 347 municipalities. This would be particularly severe in Warsaw, Kraków, and Gdańsk (Figure 3.28). The average percentage and the variability of potential losses due to flooding of land carrying roads against the total transport losses for the entire set of municipalities where these areas occur are almost identical to those for floods with a 1% (fluvial flooding) and a 10% probability. As regards the absolute value of losses due to flooding of land carrying roads, municipalities in Pomeranian Province would be in the worst situation. The largest number of municipalities that would potentially suffer losses in this scenario are in Lower Silesia. In relative terms, the highest average percentage of possible losses in land carrying roads against the total transport losses applies to municipalities in Opole Province (85.32%).

The highest percentage of possible losses in land carrying roads for vehicular traffic (against total losses for this land use) within flood hazard areas applies to the water region of the Upper Eastern Vistula (for both areas at high and medium risk of flooding). In both scenarios, a flood in this region could inundate more than a quarter of the areas in question. As for the areas where there is a 1% probability of coastal flooding and where there is a risk of flooding due to a complete breach of the protective structure of the service strip, roads running through municipalities in the water region of the Lower Vistula are definitely most at risk. By contrast, in the water region of the Upper Western Vistula it would be a breach of stopbanks that could bring the most severe consequences as regards possible economic losses in land carrying roads for vehicular traffic (Table 3.6).

Table 3.6. The magnitude of losses due to flooding of land carrying roads for vehicular traffic by water region and the percentage of their surface area within the total surface area of such land in Poland in 2019 [%]

Flood scenario	The magnitude of losses due to flooding of land carrying roads for vehicular traffic [%]													Percentage of the surface area of inundated land carrying roads for vehicular traffic against the total surface area of such land in Poland [%]
	the Vistula basin							the Oder basin					the Pregolya basin	
	the Bug water region	the Lower Vistula water region	the Upper Eastern Vistula water region	the Upper Western Vistula water region	the Little Vistula water region	the Narew water region	the Middle Vistula water region	the Lower Oder and the coastal strip of West Pomerania water region	the Upper Oder water region	the Noteć water region	the Middle Oder water region	the Warta water region	the Łyna and the Węgorapa water region	
10%	5.08	8.62	26.15	13.47	0.85	1.94	6.55	1.88	6.48	0.62	15.71	12.63	0.01	0.19
1%	3.61	3.83	27.16	9.03	2.17	1.61	7.22	1.41	11.63	0.48	25.40	6.44	0.00	0.67
1%C	–	79.91	–	–	–	–	–	20.09	–	–	–	–	–	0.03
SSB	–	97.17	–	–	–	–	–	2.83	–	–	–	–	–	0.15
SB	0.16	21.98	4.13	27.69	2.01	0.42	17.17	0.59	3.83	0.13	15.96	5.94	0.00	1.55

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

3.2.2. Population distribution

Besides analysing areas where land use may indirectly affect the operation of road transport by changing the demand for transport (industrial facilities, etc.), and the location of transport infrastructure (including roads), it is also crucial to examine data on the number and distribution of the population in areas at risk of flooding in each scenario. The degree of detail this offers (the number of occupants registered for each building in the areas at risk) allows the researcher to tangibly improve the methodology of studying how flood-related changes impact the operation of road transport in respect to transport accessibility or road network load.

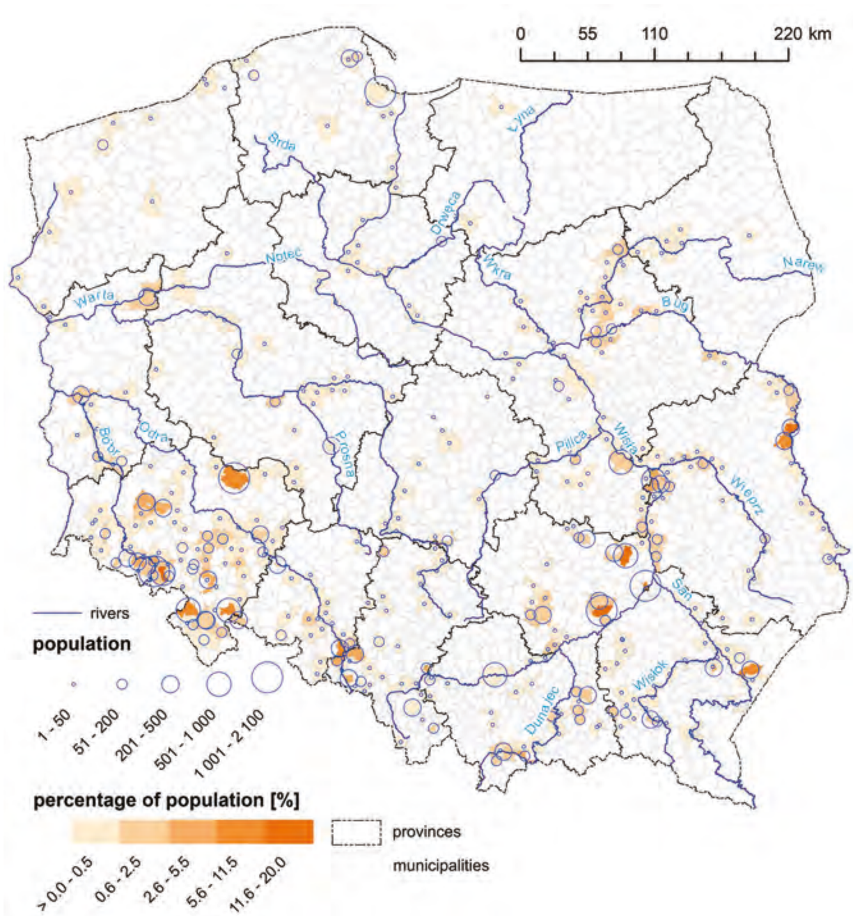

Figure 3.29. The number of residents living in areas where there is a 10% probability of flooding and the percentage of the population there against the total population of the municipalities in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Local Data Bank by the Central Statistical Office

A total of 30,548 people reside in areas at high risk of flooding, and a total of 394 municipalities are affected. Over half of these (56.5%) live in the flood hazard areas within the basin of the Vistula, while the remaining population resides in the basin of the Oder. As for the Pregolya, there is no population living in the areas at high risk of flooding. The analysis of the areas in question on the scale of municipality reveals that the largest population lives in Sandomierz, followed by Gdańsk (Figure 3.29). In addition, a large percentage of the population in areas at high risk of flooding (against the total population of the municipality) resides in municipalities in Lower Silesian Province (Figure 3.29).

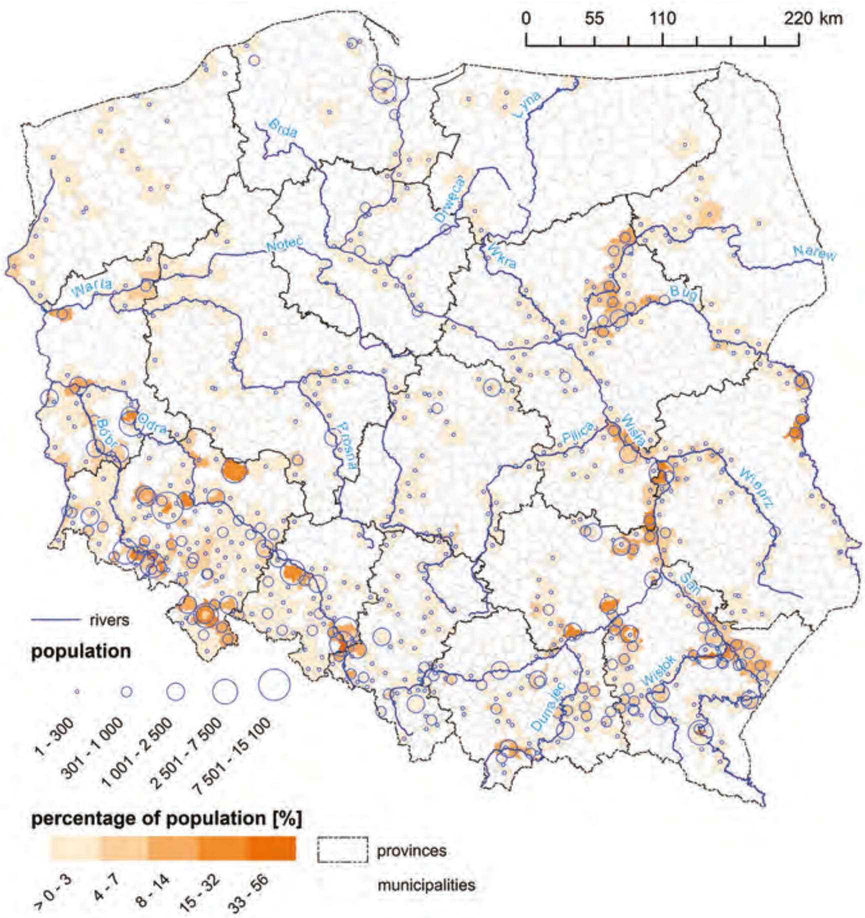

Figure 3.30. The number of residents living in areas where there is a 1% probability of fluvial flooding and the percentage of the population there against the total population of municipalities in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Local Data Bank by the Central Statistical Office

A total of 223,600 people reside in areas where there is a medium probability of flooding. In this scenario, the population would be at risk in as many as 709 municipalities, with the situation being exceptionally severe in Legnica and Sanok. On a regional scale, there would be a large number of municipalities and a significant percentage of the total population at risk in Lower Silesia, Subcarpathia and Masovia (Figure 3.30).

A total of 16,358 people reside in the 35 municipalities within areas where there is a medium probability of coastal flooding. In absolute terms, Gdańsk is particularly affected, where the population living in areas where there is a 1% probability of coastal flooding is over three times higher than in Świnoujście, which is ranked second (Figure 3.31).

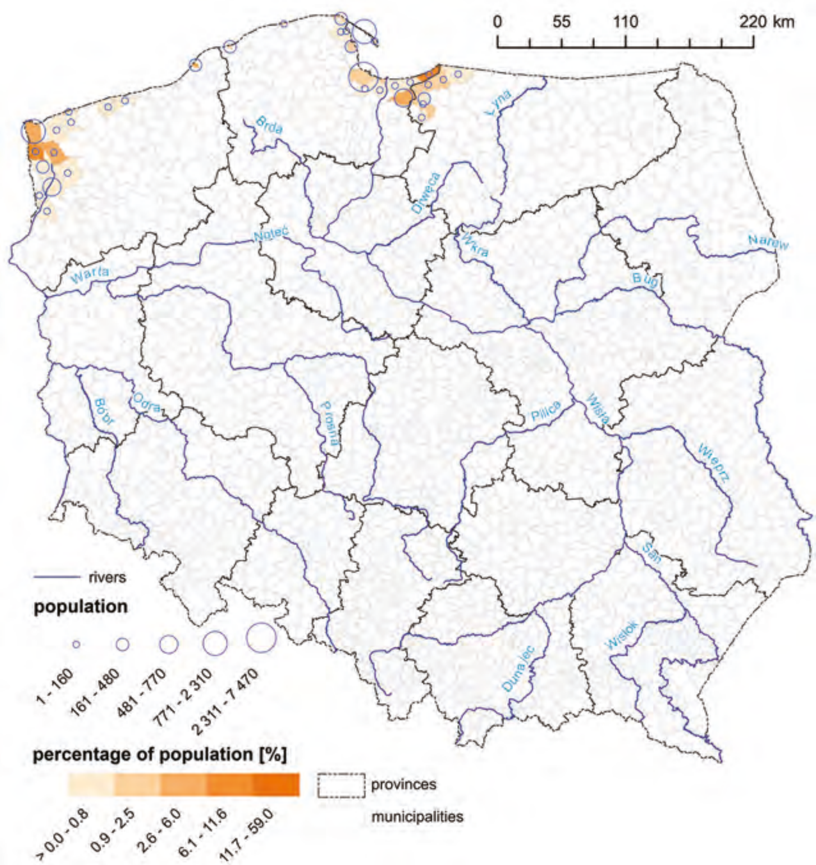

Figure 3.31. The number of residents living in areas where there is a 1% probability of coastal flooding and the percentage of the population there against the total population of municipalities in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Local Data Bank by the Central Statistical Office

In 29 municipalities there are 37,884 residents who are at risk of flooding due to a complete breach of the protective structure of the service strip. The municipality of Nowy Dwór Gdański is in a particularly unfavourable situation, as over two and a half times more people would be in danger there than in Gdańsk, which is ranked second in this respect (Figure 3.32).

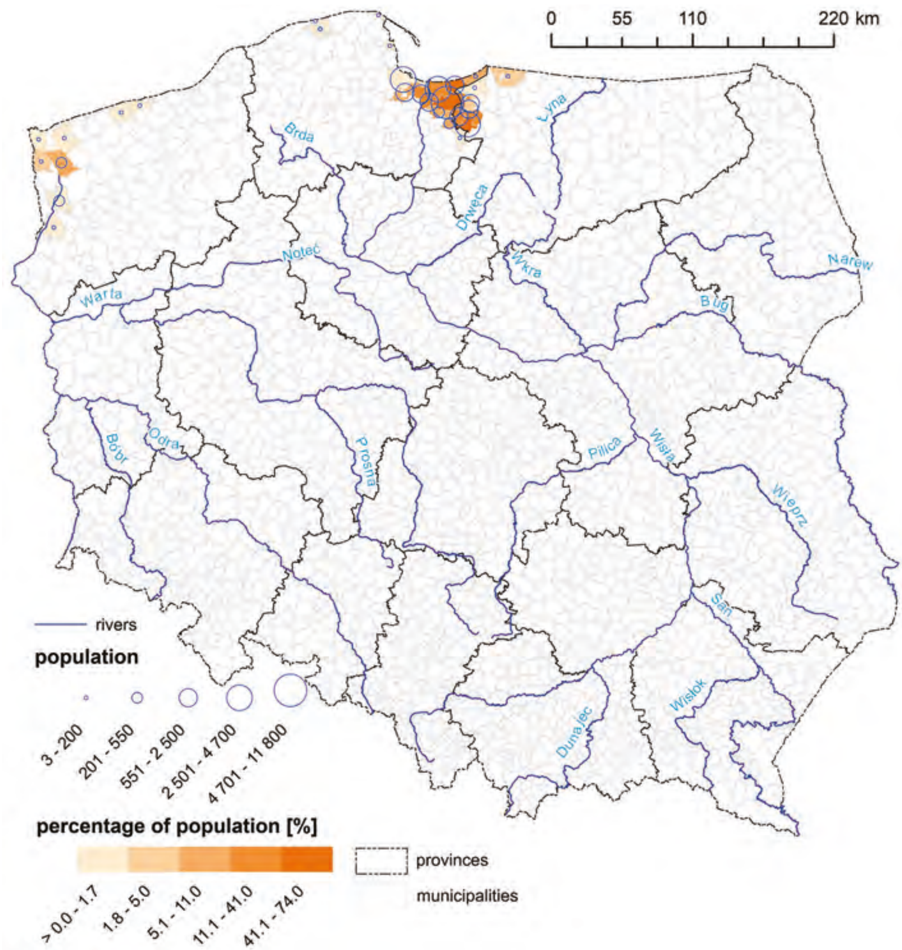

Figure 3.32. The number of residents living in areas at risk of flooding due to a complete breach of the protective structure of the service strip and the percentage of the population there against the total population of municipalities in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Local Data Bank by the Central Statistical Office

The scenario in which a flood occurs in areas at risk due to a complete breach of a stopbank poses the greatest threat to the health and life of the population, since as many as 932,290 people reside therein. However, when compared to the second worst-case scenario (a fluvial flood with a 1% probability of occurrence), this threat appears more "concentrated" as it affects just 397 municipalities. A staggering 81% of the total population residing within the areas in question live in the basin of the Vistula. The problem is particularly worrying in Warsaw, where the population living in areas at risk of flooding due to a complete breach of a stopbank is over two and a half times greater than in Kraków, which ranks second (Figure 3.33).

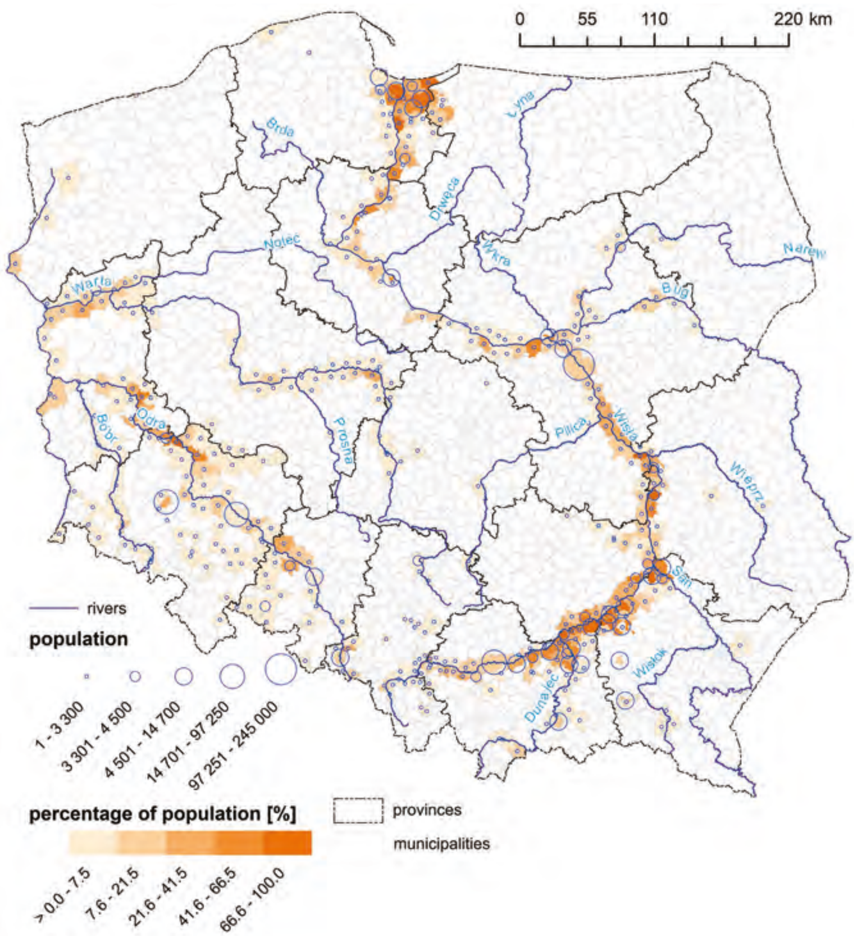

Figure 3.33. The number of residents living in areas at risk of flooding due to a complete breach of a stopbank and the percentage of the population there against the total population of municipalities in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Local Data Bank by the Central Statistical Office

The analysis of the percentage of the population residing in areas at high or medium risk of flooding by water region clearly shows that the water region of the Middle Oder stands out in this respect. As for areas where there is a 1% probability of coastal flooding and areas at risk of flooding due to a complete breach of the protective structure of the service strip, the situation is particularly unfavourable in the water region of the Lower Vistula. Finally, the analysis of the percentage of the population residing in areas at risk of flooding due to a complete breach of a stopbank reveals that the water region of the Middle Vistula stands out, accounting for over a third of the population at risk in this scenario. A breach of stopbanks would also have grave consequences in the water region of the Upper Western Vistula, where over a quarter of the total population at risk in this scenario resides (Table 3.7).

Table 3.7. The spatial structure of the population in flood hazard areas by river basin and water region in Poland in 2019 [%]

River basin	Water region	Flood scenario				
		10%	1%	1%C	SSB	SB
the Vistula	the Bug	4.19	3.11	–	–	0.81
	the Lower Vistula	7.03	4.94	74.31	97.27	10.63
	the Upper Eastern Vistula	6.58	18.73	–	–	5.94
	the Upper Western Vistula	21.34	10.27	–	–	27.13
	the Little Vistula	1.43	1.95	–	–	1.34
	the Narew	0.91	2.02	–	–	0.45
	the Middle Vistula	15.01	9.53	–	–	34.72
the Oder	the Lower Oder and the coastal strip of West Pomerania	0.66	0.81	25.69	2.73	0.08
	the Upper Oder	6.86	8.99	–	–	2.41
	the Noteć	0.93	0.33	–	–	0.09
	the Middle Oder	31.86	36.88	–	–	12.63
	the Warta	3.18	2.39	–	–	3.78
the Pregolya	the Łyna and the Węgorapa	–	0.05	–	–	–

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019).

Having data on the number and distribution of the population in flood hazard areas in the analysed scenarios is important for studying transport accessibility and road network load during an emergency situation. The incorporation of this data can affect the generation potential of individual transport regions and the volume of traffic flows. The monograph relies on this data to reduce the population of municipalities when applying the potential-based methodology for studying transport accessibility. This data was also taken into account to reduce traffic generation potentials when the changes in road network load accompanying a flood event were analysed. This data is also crucial when implementing measures to organise the process of evacuation, as the vehicle traffic that accompanies it can affect road conditions.

3.3. Legal and administrative frameworks for the management of flood hazard areas

The relevance of the legal restrictions on land use in flood hazard areas for the operation and development of the road networks located therein can be viewed from two perspectives. On the one hand, the degree of liberty in land use in floodplains indirectly affects transport demand, and transport demand is an important stimulant for the development of the road network. On the other hand, restrictions in land use may reduce the attractiveness of the area as a potential trip destination, thereby diminishing the relevance of the sections of the road network located there, particularly on a local scale (a drop in the number of network users). However, this effect has little impact on road sections serving transit traffic that run through flood hazard areas and are essential for the effective operation of the transport network addressing needs on a supra-local scale. Besides the current legal directives in this matter, it is also vital to understand the evolution of the laws governing the management of areas at risk, since a large part of the existing road network was designed and implemented pursuant to legal provisions valid at the time when these roads were built.

In Poland, floods are among those natural disasters that generate the highest economic losses (Kułakowska-Bicz 2011, Ostrowski et al. 2012, Franczak et al. 2016). These losses primarily stem from inappropriate land use in flood hazard areas, which is due to either imprecise or non-existent spatial planning within these areas (Franczak et al. 2016). The main causes behind the high losses from floods on floodplains include:

- dense development (mainly urban) and the presence of technical infrastructure (including transport) in areas at risk,
- the significant reduction or complete suppression of water infiltration due to the trends that promote sealing the land surface (Skrzypczak et al. 2015).

The main objectives of flood protection to date have been the protection of people and mitigation of flood-related losses through flood protection measures that have focussed on the application of technical devices (Bobiński and Żelaziński 1996, Bajorek 2001), on the assumption that poor hydrotechnical development of river valleys impedes the effective prevention of large (and even catastrophic) floods and inhibits the protection of the population and their property (Grochulski 1975). Unfortunately, long-term observations have revealed that this practice has often failed, and unwarranted trust in the reliability of these devices has only exacerbated the threat to life (Bobiński and Żelaziński 1996). This approach has also ignored the environmental aspect (Borowska-Stefańska 2015b). Alongside technical and environmental aspects of flood protection, laws and regulations relevant to land use are equally important in mitigating the adverse impact of flooding, including:

- restricting development in floodplains and the compulsory purchase of existing properties there;
- upgrading the flood resilience of facilities in flood hazard areas;
- implementing flood warning systems;
- preparing flood response plans, especially rescue and evacuation plans;
- drafting and adopting legal acts regulating flood protection (e.g., the implementation of the Floods Directive);
- appropriate spatial planning (local plans for land use and development that take into account the data from flood hazard maps and flood risk maps);
- educating the population on how to implement flood protection;
- introducing a risk-based flood insurance system;
- active participation of the National Water Management Authority, regional water management boards, and emergency management teams at a national and provincial level to co-ordinate the efforts of the fire service, police and military.

The effectiveness of these measures is dependent upon knowledge of the area at risk of flooding (in the event of a surge that reaches the value of design flow). For this purpose, the flood risk maps developed as part of the IT Country Protection System should be invaluable (Jarzębińska 2006, Flooding in Wales... 2009).

A competent spatial policy is a crucial instrument to mitigate the effects of flooding (Słysz and Pawłowska 2010, Halama 2013a) and should take into consideration environmental conditions, including restrictions on intensive land use in floodplains. Alas, such spatial policies inevitably lead to conflicts of interest with landowners who, despite being aware of the risk, still wish to develop these areas. Since the implementation of constraints on land use in flood hazard areas obviously reduces the value of land there, areas at risk of flooding have often still been earmarked for development in local spatial plans (Halama 2013a, 2013b; Borowska-Stefańska 2014; Franczak et al. 2016). According to Wołoszyn (2006, p. 157):

> The most effective method of flood protection is to stop any land use and development within floodplains that is susceptible to flood damage. However, the sound principle of "moving people away from water" can only be applied to a limited extent. Both in Poland and elsewhere, historic cities and civilisation hubs have developed

> in river valleys, often on floodplains. It is unrealistic to relocate endangered cities and settlements to a safe area. On the other hand, it remains possible and necessary to curb future development in floodplains. This is a challenging legislative problem, not always acknowledged by policy makers and urban planners.

Borowska-Stefańska et al. (2020b) confirm that until the early 2000s, flood hazard areas were not explicitly defined by law, which resulted in inadequate protection from intensive development. It was only after Poland joined the European Union and the need to implement EU regulations arose that the provisions of the Floods Directive (Borowska-Stefańska et al. 2020b) were adopted and more effective restrictions on land use and development in flood hazard areas were introduced.

In the years 1990–2001, land use in floodplains was mainly governed by the Act of 24 October 1974 – Water Law (Journal of Laws, No. 38, Item 230, as amended), which primarily protected the area between the riverbed and the stopbank (the so-called "inter-embankment zone"), where it was prohibited to erect buildings, change the relief, or install any facilities or execute any works that could impede flood protection therein. However, the act provided for an exemption from these bans by means of an administrative decision that local authorities could issue on request. The act also enabled the expansion of these restrictions to unembanked areas at risk of flooding by order of local authority (this order had the force of a local legal act). At this time, however, there were no legally stipulated regulations for recognising a given area as being at risk of flooding. Thus, land use restrictions were rarely issued by local governments and, in absence of any action in this regard that would impose specific land use (or other) restrictions on development to protect and secure people and property from floods, development continued unhindered. Pursuant to Article 58 of the said act, certain restrictions on development and land use necessary for the protection of the body of water and its use, as well as for the protection of the population and property from floods could be imposed in specified areas (Section 1). Alas, this instrument of flood protection was never used in practice, which resulted in inappropriate land use (the act remained in force until the end of 2001).

The Act of 12 July 1984 on Spatial Planning (Journal of Laws 1989, No. 17, Item 99, as amended) again contained no regulations which directly addressed flood hazard areas. However, the act did state that areas at risk of flooding could be taken into account in planning decision documents (national, regional and local spatial plans) by virtue of the provisions that spoke of "areas of elevated risk". What ensured that these provisions were respected was not only the legal requirement that decisions issued under this act were to be in line with the local spatial development plan, but also the prerequisite, arising from the provisions of the Act of 24 October 1974 – Construction Law, for granting a building permit based on previously-obtained approvals from other authorities, including water permits granted through the Water Law Act, and the aforementioned exemptions from the statutory restrictions on investments and development activities within flood hazard areas.

The Act of 7 July 1994 on Spatial Development (Journal of Laws 1999, No. 15, Item 139, as amended) did not introduce any substantial changes in restricting land use within flood hazard areas either, since the provisions in this act did not explicitly mention such areas. It was not until the Act of 18 July 2001 – Water Law (Journal of Laws 2017, Item 1121, as amended) that several significant changes were introduced to the legal model for restricting land use in flood hazard areas. This act was the first to define areas at risk of flooding, dividing them into "areas at direct risk of flooding" (including zones of flood surges defined in local plans of spatial development on the basis of flood protection studies produced by regional water management boards) and "areas at potential risk of flooding" (including those exposed to flooding in the event of water overtopping the crown of a stopbank and/or a breach of or damage to a stopbank, damming structures or protective structures of the service strip).

Importantly, under the act, areas at risk of flooding could only be considered as areas at direct risk of flooding (with all legal effects) if they were included as such in the local spatial development plan (the locations of these areas were taken from the above-mentioned flood protection studies produced by regional water management boards). If this requirement was not met, the areas identified did not gain the status of areas at direct risk of flooding. However, the fact that they had been identified in the said studies as areas at risk still had to be mentioned in decisions arrived at on the conditions of land use and development issued under this act, which was meant to make the recipient aware of the investment risk therein. However, since no executory order was ever issued to designate areas at potential risk of flooding, such areas were never formally recognised (Borowska-Stefańska et al. 2020b).

The single most important legal provision that directly affected land use in flood hazard areas during the period in question was Article 881 of the Act of 18 July 2001 – Water Law, which forbade any work or operations that could impede flood protection or increase the risk of flooding to be executed on floodplains, including the installation of water facilities and any other structures (Act of 18 July 2001 – Water Law, Journal of Laws 2001, No. 115, Item 1229, as amended; Journal of Laws 2012, Item 145, as amended). Broadly speaking, in view of the Act of 24 October 1974 – Construction Law, this provision should have imposed a complete ban on any development in the areas in question. However, it also provided for exemptions by means of an administrative decision, to be granted by heads of regional water management boards in justified cases. As a result, both in local spatial development plans and in decisions on conditions of land use and development, investment could be permitted in these areas (Flood Safety Programme in the River Basin of the Middle Vistula – Premises, 2011; Borowska-Stefańska 2015b). Importantly, if such areas were identified as at risk of flooding in the aforementioned studies, this also had to be highlighted in planning decision documents, decisions on the location of public-benefit investment projects, and decisions on the conditions outlined for land use and development. At that time, it was also mandatory to consult the head of the regional water management board over any planning decision documents which concerned lands designated as areas at risk of flooding in the said studies. This obligation was also expressed in the provisions of the Act of 27 March 2003 on Spatial Planning and Development (Borowska-Stefańska et al. 2020b).

As regards spatial development, a relevant provision on flood protection during the period in question was Article 6(4) of the Real Estate and Property Management Act of 21 August 1997, under which the development and maintenance of flood protection facilities and equipment was recognised as public benefit. Therefore, special procedures were set for their location and servicing, arising from the Act of 27 March 2003 on Spatial Planning and Development, and the Real Estate and Property Management Act (Flood Safety Programme in the River Basin of the Middle Vistula – Premises, 2011; Borowska-Stefańska 2015b).

Some (albeit not fundamental) changes were introduced by the 2005 amendment to the Water Law Act. Besides cosmetic changes to terminology (the said studies by regional water management boards were renamed "flood protection studies"), the division into areas at direct and potential risk of flooding was retained. However, several modifications were implemented to allow tougher restrictions on land use and development in flood hazard areas. Firstly, the designation of areas at potential risk of flooding (including areas exposed to flooding due to a breach of or damage to stopbanks and/or damming structures) no longer required a decree from the minister; it was then enough that these were specified in the flood protection studies. Secondly, there was now an option to expand the restrictions, which once applied exclusively to areas at direct risk, to lands at potential risk, if this was duly justified by concerns for the safety of people and property (Borowska-Stefańska et al. 2020b).

A major legal shift for flood hazard areas took place following Poland's accession to the EU and the implementation of three EU directives into Polish law: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy (Official Journal of the European Union of 22 December 2000, L 327, p. 1, as amended), Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks, also known as the Floods Directive (Official Journal of the European Union of 6 November 2007, L 288, p. 27), and Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on Environmental Quality Standards in the Field of Water Policy, Amending and Subsequently Repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC, and Amending Directive 2000/60/EC of the European Parliament and of the Council. As a result, a new system of flood protection was introduced into law, which necessitated amendments to the Water Law Act governing flood protection in Poland to make it legally compatible with the EU Directives on water management. These changes entered into force on 18 March 2011 (Act of 18 July 2001 – Water Law, Journal of Laws 2011, No. 32, Item 159) (Borowska-Stefańska et al. 2020b).

The core document that defines the objectives and principles of water management in EU countries is Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 (Głosińska 2014; Borowska-Stefańska 2015b). The implementation of Directive 2000/60/EC across all EU member states was a multi-stage process (Tsakiris et al. 2009; Barszcz et al. 2013) and all EU states were obliged to satisfy all the requirements by the end of 2015. In Poland, the first stage of the implementation, which consisted of adapting national law to the requirements of the Floods Directive, was delayed by over a year and concluded in early 2011 (Głosińska 2013). During the second stage, the preliminary flood risk assessment (PFRA), produced in late December 2011, was designed to assess the scale of flood hazard for river basins and to identify places where flood risk was elevated (Tokarczyk et al. 2012). Next, this data was used to determine those river sections for which flood hazard maps and flood risk maps were to be produced (2013) (Borowska-Stefańska 2015b) based on the guidelines in the Ordinance of the Minister of the Environment, the Minister of Transport, Construction and Maritime Economy, the Minister of Administration and Digitisation, and the Minister of the Interior of 21 December 2012 on the Preparation of Flood Hazard Maps and Flood Risk Maps. The main purpose behind these maps was a better understanding of the flood intensity and the magnitude of flood risk in the areas in question (Kurczyński 2012).

The flood hazard maps show:

1. Areas with a low probability of flooding (once in 500 years) or areas where there is a probability of an extreme event;
2. Areas at elevated risk of flooding (previously defined as areas at direct risk of flooding);
3. Areas which include land at risk of flooding in the event of:
   – water overtopping the crown of a stopbank,
   – a breach of or damage to a stopbank,

– a breach of or damage to damming structures,
– a breach of or damage to the protective structure of the service strip.

For the areas in question, the flood hazard maps present:

- the scope of flooding,
- water depth or water table level,
- the velocity or intensity of the water flow (where applicable).

These maps were prepared under two thematic sets:

- flood hazard maps showing water depth;
- flood hazard maps showing velocities and directions of the water flow.

The flood risk maps, which were prepared for flood hazard areas (late December 2013) and show the potential negative effects of flooding, were also divided into two thematic sets:

- flood risk maps showing the threat to the population and possible flood-related losses,
- flood risk maps showing land use and areas/facilities of special cultural, natural, economic value (Act of 18 July 2001 – Water Law, Journal of Laws 2017, Item 1121, as amended; Borowska-Stefańska 2016, pp. 122–123).

The final stage in the implementation of the Floods Directive was the creation of flood risk management plans in late 2015 (Borowska-Stefańska 2014, Borowska-Stefańska 2016), developed for two specific levels: river basins and water regions (Borowska-Stefańska 2016).

The changes brought new terminology for flood hazard areas. Under the Water Law Act (Act of 18 July 2001 – Water Law, Journal of Laws 2001, No. 115, Item 1229, as amended; Journal of Laws 2012, Item 145, as amended), areas at risk of flooding were considered to be "areas identified by the preliminary flood risk assessment where a significant flood risk exists or is likely to occur." These areas included:

1. Areas where there is a low probability of flooding (once in 500 years) or where there is a probability of an extreme event.
2. Areas at elevated risk of flooding, namely:
   – areas where there is a medium probability of flooding (once in 100 years);
   – areas where there is a high probability of flooding (once in 10 years; part of the 100-year floodplains);
   – areas between shoreline and an embankment or a natural high shore incorporating an embankment, as well as islands and alluvial banks (referred to in Article 18 of Water Law Act) which are registered as separate parcels of land;
   – a service strip (referred to in Article 36 of the Act of 21 March 1991 on Maritime Territories of the Republic of Poland and Maritime Administration).

3. Lands that include areas at risk of flooding (areas potentially at risk of flooding) due to:

– a breach of or damage to an embankment;

– a breach of or damage to a seashore embankment (Act of 18 July 2001 – Water Law, Journal of Laws 2001, No. 115, item 1229, as amended).

A key component of flood protection, both flood hazard and flood risk maps had to be taken into account when drafting (general and individual) planning decision documents, including the national spatial development strategy, provincial and local spatial development plans, decisions on the location of public-benefit investment projects, and decisions on the conditions set for land use and development. Any changes to these documents had to be made within 18 months from the date when these maps were made available to local governments. From that date, all decisions on the location of public-benefit investment projects and decisions on the conditions set for land use and development in flood hazard areas had to take into consideration the level of flood hazard indicated therein. Flood hazard maps and flood risk maps are updated every six years (Borowska-Stefańska 2015b). Regrettably, on 31 December 2015, the legal obligation to include the boundaries of flood hazard areas and flood risk levels derived from these maps in planning decision documents was abolished and replaced with the mere "possibility" to do so, which must be seen as a regression in the field of flood protection (Borowska-Stefańska et al. 2020b).

Alas, the growing number of acts to facilitate greater protective measures against the effects of flooding did not lead to significant changes in the existing pattern and substance of restrictions on land use and development in flood hazard areas. Restrictions stipulated in the Act of 18 July 2001 applied exclusively to areas at elevated risk of flooding, and imposed a ban on construction or any other activity that could impede flood protection or increase the risk of flooding there, including the construction of water facilities and any other structures, with the exception of cycle paths. In addition, the legislator preserved the possibility of exemptions from these bans. By means of an administrative order, any competent body was eligible to resolve a given case by determining individual conditions of flood protection if this did not impair flood risk management.

The relevance of the Act in the context of the above-mentioned obligation to take into account areas at elevated risk of flooding in local spatial development plans must be considered, and especially the problem of determining the permissible types of land use there, e.g., permitting development under individually-specified conditions. Judicial decisions by administrative courts (which are bodies considered competent to adjudicate on complaints against the provisions within the plans) have established the guideline that a ban on building structures and facilities in these areas, as stipulated in the Water Law

Act, must be incorporated early (i.e., when local spatial development plans are adopted) and must lead to an official prohibition on land use and development therein (Borowska-Stefańska et al. 2020b).

In 2018, further legal amendments were implemented that are relevant to the spatial policy on flood hazard areas. On 1 January 2018, a new water law act (Act of 20 July 2017 – Water Law, Journal of Laws 2018, Item 2268) entered into force, preserving the flood protection model shaped by the previous act (e.g., the system of planning decision documents and permits), which stemmed from the implementation of EU law. While the new act did not change the existing principles and methods of defining flood hazard areas, it did introduce slight corrections to the terminology; namely, areas at risk of flooding were now defined "areas identified in the preliminary flood risk assessment where there is a high risk of flooding or where a high risk of flooding is probable" (Article 16, Item 33 of the Act of 20 July 2017 – Water Law, Journal of Laws 2018, Item 2268; Journal of Laws 2019, Items 125, 534). For these areas, flood hazard maps were produced, showing:

1. Areas where there is a low probability of flooding (0.2%) or where there is a probability of an extreme event.
2. Areas at elevated risk of flooding (Article 16, Item 34):
   a) areas where there is a medium (1%) probability of flooding;
   b) areas where there is a high (10%) probability of flooding (within areas where the corresponding probability is 1%);
   c) areas between shoreline and an embankment or a natural high shore incorporating an embankment, as well as islands and alluvial banks (referred to in Article 224 of Water Law Act) which are registered as separate parcels of land;
   d) service strips.
3. Lands that include areas at risk of flooding due to a breach of or damage to:
   a) an embankment;
   b) a seashore embankment;
   c) damming structure (Act of 20 July 2017 – Water Law, Article 169, Section 2).

Importantly, from 1 January 2018 the State Water Holding Polish Waters (state-controlled legal entity) is entitled to review local spatial development plans and assess decisions on land use and development in areas at elevated risk of flooding (1% probability) (Ilba 2018, Borowska-Stefańska et al. 2020b). As regards development and land use in such areas, all proposed local decisions must be consulted with the State Water Holding Polish Waters, so that it could issue an administrative decision that specifies the requirements or conditions for the planned development and land use in a given area at risk of flooding.

3.4. Regulations for the development and management of road infrastructure in flood hazard areas

Although land use is generally restricted in flood hazard areas, it may, at times, be necessary to develop the road network there or to run new road sections vital to the operation of the larger transport network. The appropriate design, construction, and maintenance of the road infrastructure in such areas is then essential since they may be exposed to a number of hazards (see: Subchapter 2.2.3).

Investments in road transport infrastructure may include construction of a new route or arise from the need to replace existing infrastructure, especially if the existing infrastructure fails to meet the parameters for either the current or predicted requirements of capacity or safety (insufficient load-bearing capacity, etc.). Sometimes only the renovation or reconstruction of a given infrastructure is involved, although this still means that its technical specifications must fulfil the technical parameters of the longer route it is part of (vertical and horizontal alignment, load-bearing capacity, cross-section, etc.) (Madaj and Wołowicki 2003). Deviations in that matter are only acceptable when a given infrastructure is being renovated (modernised).

When a road or an engineering structure (a bridge, etc.) expected to be exposed to the impact of a watercourse is being designed, analyses to determine the magnitude of the impact must be conducted (e.g., the minimum required bridge clearance[7]). For this purpose, it is imperative to collect data on the cross-section of the watercourse and the floodplain, the characteristics of the watercourse, the size of the catchment area, the geological structure of the watercourse bed and the floodplain, the vegetation found therein, etc. (Madaj and Wołowicki 2003). The analytical capacity is largely determined by the available geodetic documentation (topography and elevation maps, watercourse cross-sections, longitudinal profile and gradient, etc.). The breadth of the analyses also stems from the spatial and morphological conditions of the projected infrastructure and its importance for the operation of the entire road network.

Guidelines and good practices for the design and construction of road infrastructure exposed to floodwater are embedded in legal provisions and other directives from infrastructure bodies. These include the Ordinance of the Minister

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[7] Distance between the abutment walls measured for the design elevation of water surface and reduced by the total thickness of the piers at that level. For bridges without abutments or with integral abutments, it is the distance between the reinforcements of the slopes of the embankment cones, measured for the design elevation of high water level and reduced by the total thickness of the piers at that level. Bridge clearance is measured in a plane perpendicular to the watercourse (Act of 21 March 1985 on Public Roads, Journal of Laws 1985, No. 14, Item 60, as amended).

of Transport and Maritime Economy of 30 May 2000 on Technical Specifications to Be Met by Road Engineering Structures and Their Location (Journal of Laws 2000, No. 63, Item 735, as amended), which lists, inter alia, the requirements for the protection of bridges against the effects of flooding. When designing, constructing and rebuilding engineering structures, the provisions of Article 1(3) apply, stating that the technical specifications – with observance to the provisions of Construction Law, the regulations on public roads, as well as the provisions of Polish construction standards and other acts – ensure the safety of engineering structures, especially as regards the possibility of fire, flooding, ice flow, collisions with vessels and vehicles, and the impact of mining operations (Section 3.2). An engineering structure should be designed and constructed in accordance with the constraints arising from its location and purpose, so that its durability is ensured and the conditions for proper operation and maintenance are met. When implementing a technical design for a given structure, the designer is obliged to take into account the location of the structure and the water conditions therein, and to perform the relevant hydraulic calculations.

Chapter Two of the ordinance states that the suitability of engineering structures for the terrain is determined by the required clearance based on the location of the bridge. According to Article 18(1), the length of the bridge should result from the prerequisite of a minimum bridge clearance that ensures free design flow with no excessive obstruction of the watercourse. By way of example, Article 18(3) provides that the design flow is the maximum annual flow whose probability of being exceeded equals 0.3% for bridges located on MW (motorways), EW (expressways) and FTTR (fast traffic trunk roads); 0.5% for MR (main roads) and CR (collector roads); and 1% for LR (local roads) and AR (access roads). Hydraulic calculations and requirements similar to those for culverts (Article 38) should apply to small bridges. In this case, the ordinance specifies the following levels of probability value to be taken into account when calculating the design flow: for MW, EW, FTTR, MR and CR – 1%, and for LR and AR – 3%. The probability value to be adopted depends on the category of the road along which the bridge or culvert is located, following the principle that the higher the road category, the lower probability of events is applied in the design of this structure.

Article 23(1) states that when the expected ice flow has the same value as the design flow, then for a bridge with the clearance smaller than 30 metres the calculations should be based on this flow but increased by 15% of its value. Article 23(2) specifies that on montane streams, submontane rivers, and on the sections of watercourses that connect them, the bridge clearance should be increased by 15% of the value calculated, while bridges with a clearance of less than 25 metres should be single-span structures, pursuant to Article 23(2.2). The design flow for bridges located on embanked rivers should respect the requirements of flood protection for the river section in question (Article 19).

Madej and Wołowicki (2003, p. 66) state that bridge clearance calculations are performed to "determine the horizontal dimensions of the undeveloped watercourse that ensure the safe high water design flow, i.e., a flow that poses no threat to the structure and the adjacent land". Calculations for culverts should also take into account the size and shape of the cross-section. Although the methodology for determining the clearance largely depends on the size of the structure, it is generally based on calculating the minimum clearance, the position of abutments and supports (and their dimensions), and the calculation of anticipated scour and damming. This data is then juxtaposed against the requirements that the bridge must meet for acceptable water flow velocity, bed scour, water damming, and minimum elevation of the structure above high water level. Bridge cross-sections are therefore designed to withstand a flow of a specified probability of overtopping, which represents the safety benchmark of a given structure. For instance, the minimum elevation of the bridge above the maximum level of dammed water for inland non-navigable waters must be at least 50 cm[8] (additional provisions apply to different structures, e.g., bridges built of rust-resistant steel).

When a bridge is built over a watercourse, the space underneath must be designed so that it allows ice floes and water to flow smoothly (especially during floods). The method of choice to find the bridge clearance that ensures this is hydraulic modelling. In order to ensure the safety of a bridge, it is crucial that the structure is properly distributed over the spans as the flow of water and ice floes can also be obstructed by the spans.

In line with good design practices, the required elevation of a bridge over the water level is calculated using the water level upstream of the structure, which may be increased by the wave height and the wind-induced (eolian) water level rise. Wind-induced damming of water[9] must be taken into account in estuarine sections of rivers flowing into the sea and in sections of watercourses flowing into or out of natural or artificial reservoirs (Madaj and Wołowicki 2003).

The location and parameters of the bridge always depend on the transport route along which the structure is built. The design of small engineering structures (e.g., small bridges[10]) depends entirely (in terms of location and parameters) on the course of the transport route to be functionally and economically optimal

[8] One metre for waters considered floatable and on non-floatable watercourses; half a metre on other non-navigable waters; one and a half metres on waters considered navigable, under unnavigable spans.

[9] A wind velocity of 20 m/s and a wave height with a 1% probability of occurrence are applied as design values.

[10] An engineering structure whose clearance does not exceed 10 metres and where the riverbed under and downstream of the bridge is protected from scour.

(Madaj and Wołowicki 2003), while large and critically important structures are not as strictly determined by the transport route. These usually require specific site conditions to ensure a high level of stability and robustness, which justifies a diversion of the route itself.

Good safety practices for the road networks also require that calculations be made for water flows that are higher than design values (e.g., by 20 or 40%), and that water flows whose probability is lower than those indicated in the legislation be included in the calculations. It is also crucial to verify the calculations by comparing them with the results of actual observations – especially during floods (Madaj and Wołowicki 2003).

Pursuant to the Act of 10 April 2003 on Special Principles of Preparation and Execution of Investments in Public Roads (Journal of Laws 2003, No. 80, Item 721, as amended), an application for a permit to execute a road investment must include the opinion of a regional water management board (part of the State Water Holding Polish Waters), concerning structures in areas at elevated risk of flooding. This opinion is issued at the request of the road authority. Failure to issue an opinion prior to the statutory deadline is deemed as consent. If the implementation of a road project requires a permit required by the Water Law Act, either the State Water Holding Polish Waters or the minister responsible for water management consider its issuance. Pursuant to the Act of 20 July 2017 – Water Law (Journal of Laws 2017, Item 1566, as amended), consent is never denied for bridges that are to be entirely or partly erected in areas at elevated risk of flooding provided that their erection is necessary to maintain the continuity of existing or planned transport routes, even if these investments violate the provisions of the river basin management and flood risk management plans; pose a threat to the protection of human health, the environment or cultural assets listed in the Registry of Cultural Property; and impede the effectiveness of critical infrastructure or flood risk management.

Pursuant to Article 36(1) of the Ordinance of the Minister of Transport and Maritime Economy of 30 May 2000 on Technical Specifications to Be Met by Road Engineering Structures and their Location, in areas where elevated road sections cut through river floodplains, the construction of flood embankments is necessary if the flow in the floodplain is greater than 15% of the total design flow, the average water flow velocity is greater than 0.6 m/s, and the elevated road section parts the floodplain along more than one-third of its width. Pursuant to Article 36(2) therein, another prerequisite is the frequency of overtopping which should be forecast to happen at least once every three years.

As regards building developments in areas at elevated risk of flooding, the Ordinance of the Minister of Maritime Affairs and Inland Navigation and the Minister of Investment and Development of 24 January 2019 on Requirements that a Permit Required by Water Law Act May Specify for

Structures and Buildings Located in Areas at Elevated Risk of Flooding (Journal of Laws 2019, Item 227) stipulates that the permit may specify the building materials and architectural solutions concerning, inter alia, the structure with regard to its resistance to the pressure of water and ice floe, the height at which the floor of the lowest storey should be located above the level of water (calculated for a flood with a 1% probability of occurrence), the technology applied for the foundations of the structure depending on the scope and depth of water (calculated for a flood with a 1% probability of occurrence). The Ordinance of the Minister of Maritime Affairs and Inland Navigation and the Minister of Investment and Development of 24 January 2019 on the Scope of Requirements and Conditions for Planned Development and Land Use of Areas Located within Areas at Elevated Risk of Flooding and the Manner of Their Determination (Journal of Laws 2019, Item 244) specifies the measures to mitigate the negative effects of flooding, including the principles of development of road systems in residential, commercial and agricultural areas, including those roads earmarked for evacuation.

The above provisions show that the legal documentation for road investments allows for the possibility to run a road through an area at elevated risk of flooding. A review of the existing planning decisions provided by the relevant authorities reveals that a significant number of such cases involve roads crossing a river via a bridge. If this is the case, it is obligatory to comply with the Ordinance of the Minister of Transport and Maritime Economy of 30 May 2000 on Technical Specifications to Be Met by Road Engineering Structures and Their Location, pursuant to which the technical specifications and design of a bridge must take into account the design flow.

If the legal framework includes areas at elevated risk of flooding with a 1% probability of occurrence (once in a 100 years), then, when correctly applied, the principles of normative design of engineering structures protect bridges and access roads from flooding. Past design practice shows that areas at elevated risk of flooding are primarily taken into consideration only when designing drainage systems for road sections, i.e., settling tanks and separators of the sewer system are placed above the elevation of such areas and non-return flap valves are installed at sewer outlets to prevent backflow of water from the watercourse and into the sewer collectors.

New road investment projects take into account the course of the transport route in areas at elevated risk of flooding, but ignore all other, less likely, flood scenarios, e.g., areas at risk of flooding once in 500 years or due to a breach of a stopbank. Thus, one can assume that new road developments within areas at elevated risk of flooding can withstand a flood with a 1% probability of occurrence. As regards the construction of roads and engineering structures in areas at elevated risk of flooding, regional water management boards issue permits required by Water Law Act mainly for new structures including those that cross watercourses, inland waterways, etc. The decision to issue such a permit is based on a Water Impact Assessment (WIA), which assesses the design solutions applied and their impact on flood protection; however, the WIA is still just an assessment of the design solution, not the imposition of specific requirements. Safety issues concerning the road and its use must be resolved by the designer, as it is their responsibility to ensure that the road can be used safely in flood hazard areas as stipulated in the regulations on occupational liability for the construction industry. Regional water management boards take any increase in flood risk into consideration when assessing new road proposals, and if a new road is likely to cause water to dam up, thereby threatening residential areas, etc., measures should be taken to eliminate this negative effect (flyovers, culverts, etc.).

The State Water Holding Polish Waters is an entity that can only assess the implementation concept, and not a body that can impose flood protection requirements, and its role is restricted only to areas at elevated risk of flooding, since roads outside these lands are within the remit of neither the State Water Holding Polish Waters nor its regional water management boards. During the analysis of a given planned road development, the following are also assessed: its impact on adjacent lands; the necessity to construct bridges, culverts, and other devices to retain the water flow in the river valley; the influence of any reduced valley retention by road embankments on the concentration of water flow and the effects this has on downstream reaches of the river (localised floodings, etc.).

A specific elevation of water with a specified probability of occurrence is provided at the design stage by the relevant agencies, and the design conditions to be met are defined by norms, standards and guidelines depending on the road class, terrain conditions, effects on other transport infrastructure and the parameters required by the ordering party. Water depth data derived from flood hazard maps is supplementary, as is information on water flow velocity. These are merely indicators of the risk level, which can differ greatly. For instance, shallow waters travelling at low speeds pose little threat to people, but water that is approximately 2 metres deep and flows at 2 m/s is already capable of carrying away vehicles, thus indicating a substantial risk level.

When a road impinges on a watercourse, it most commonly runs over the water (across a bridge, etc.). In such cases, there are often separate regulations that obligate designers to consult their planned structures with competent watercourse managers, e.g., the Act of 21 December 2000 on Inland Navigation (Journal of Laws 2001, No. 5, Item 43).

Broadly speaking, a review of changes to legal provisions, including amendments that provide a more precise legal definition of areas at elevated risk of flooding, proves that all these measures have not had a significant impact on the process of issuing decisions on the design and construction of road infrastructure.

While this is not the subject of this publication, a brief mention must be made on the impact investments in transport infrastructure have on the natural environment. For instance, when a valley is narrowed by a bridge of insufficient span, it can lead to the erosion of the riverbed directly below the structure, thus necessitating the localised regulation of the watercourse, exacerbating the effect of water flow canalisation. Jeleński (2004) argues that such adverse effects can be prevented if bridges are built over the valley (or at least above the bulk of the floodplain), and the valley and the river itself can retain its natural character for aquatic and terrestrial animals (and as river or riverbank recreation routes). Construction on local roads is particularly troublesome in this matter, as – due to limited funds – implemented projects cannot usually be afforded that support the needs of the natural environment, making such road engineering structures the most common and permanent (hydraulic and ecological) obstacles in watercourse corridors (Jeleński 2004).

Besides good design and construction, the safety of the road infrastructure and its users in areas at risk of flooding is also determined by guidelines on use and maintenance to be applied during and between floods. Article 20(14) of the Public Roads Act (Journal of Laws 2018, Item 2068, as amended) stipulates that road operators are obliged to "impose restrictions or close roads and road engineering structures, and to designate diversions on roads (also of different category) whenever there is an immediate threat to the safety of persons or property." What also applies here is the Decree No. 14 by the Head of the General Directorate for National Roads and Motorways of 7 July 2005 on Implementing Guidelines for the Inspection of Road Engineering Structures When Performing Periodic Inspections of Engineering Structures Managed by the General Directorate for National Roads and Motorways, involving inspection of the technical condition, suitability for use, and visual appearance of the structures and their surroundings. A vital measure for monitoring the technical condition of bridges is the so-called "periodic inspection" (a visual check conducted while patrolling the road network), which is performed to assess the threat level for a given bridge (the water level, the amount of water-borne debris upstream of the structure, etc.) and to take appropriate measures and decisions for the situation. Another document that regulates the principles for monitoring, maintaining and protecting[11] road infrastructure (including road engineering structures) is the Decree No. 56 by the Head of the General Directorate for National Roads and Motorways of 17 November 2015 on Guidelines for Inspecting National Roads.

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[11] Measures taken to prevent premature deterioration and/or downgrading of the road, reduction of its functionality, inappropriate use of the road, and deterioration of traffic safety conditions (Act of 21 March 1985 on Public Roads, Journal of Laws 1985, No. 14, Item 60).

Another factor that greatly impacts the safety of the road network and its users is the efficient flow of information, especially in the face of such dynamic phenomena as floods. One solution that provides constant timely data on the (mainly national) road infrastructure for users and operators is the network of Traffic Information Centres (TICs), consisting of a round-the-clock contact point in the headquarters of the General Directorate for National Roads and Motorways and 16 regional offices. The TICs collect and disseminate data on traffic and road conditions, including incidents that can affect road safety and traffic flow within the network (Decree No. 4 by the Head of the General Directorate for National Roads and Motorways of 11 February 2019 on the Management of Traffic Information Centres and the Rules for the Collection and Dissemination of Data on Traffic Conditions on National Roads). In the event of a non-typical event, this enables information on the affected sections of the network and the available diversions to be communicated.

The Decree No. 10 by the Head of the General Directorate for National Roads and Motorways of 26 March 2019 on the Preparation of the General Directorate for National Roads and Motorways to Perform Emergency Management Tasks lists obstructions, extreme events, and hazards that may generate emergency situations within the national road network or other infrastructure managed by the Directorate. The document states that in order to improve the effectiveness of management during a crisis, the bodies involved should be clear on their responsibilities, the implementation of which includes the release of up-to-date information. Unfortunately, while the emergency planning of the provincial road authorities represents a reasonable and uniform level of quality, the currentness and effectiveness of the guidelines prepared by the local road authorities varies greatly.

The General Directorate for National Roads and Motorways provides a long list of the effects that a flood or ice floe may have on the road network and describes the unpredictability of the disaster itself, stressing the necessity to conduct long-term observations of engineering structures and road sections at risk. Road, bridge and culvert management requires a continuously updated list of road sections and engineering structures in need of flood and ice floe protection, a list that should take into account localised flooding, the likelihood of rivers to flood, and the expected periods of flooding and ice floes drifting near a given structure. Protection includes preparation of bridges against ice floes and water run-off, as well as the assessment of losses and the repair of flood-related damage. It is also key that bridges are inspected correctly, with an assessment of the structural health of the piers, the foundations of embankments, slopes and cones, and the condition of the riverbed. For bridges with a horizontal clearance of over 100 metres, the cross-sectional profiles of the riverbed at the piers on the outflow side should be evaluated for scour around the pier footing. Experience shows (that of the General Directorate for National Roads and Motorways, provincial road authorities, etc.) that just a risk of scouring within the embankment of the road running towards the bridge may justify closing the bridge to traffic if there is a real danger of flooding.

Under the Act of 21 March 1985 on Public Roads (Journal of Laws 1985, No. 14, Item 60, as amended), the minister in charge of transport is responsible for the co-ordination of activities to address natural disasters on public roads. Among the minister's duties, the National Emergency Management Plan also lists the co-ordination of activities by subordinate institutions, including the General Directorate for National Roads and Motorways. In the event of flooding, the supervision of road and traffic management on national roads to secure the operation of road transport and to support activities aimed at restoring the continuity of operation of critical infrastructure is particularly important.

According to the National Emergency Management Plan, the most frequent effects of flooding for road transport are temporary restrictions in mobility and the necessity to evacuate; damage to infrastructure (roads, bridges, viaducts, tunnels, culverts, etc.); blocking of transport routes/hubs that disrupts or impedes transport and mobility (people cannot reach workplaces), poor access to affected areas and the resulting difficulties in any rescue operations. To eliminate and/or alleviate these effects (besides the efforts by the minister in charge of transport) the regulations also provide for the participation of the Government Centre for Security, which is obliged to prepare and update detailed criteria to identify critical infrastructure; to produce and update a list of this infrastructure, and to perform analyses and draft prognoses on possible threats to national critical infrastructure. Another body obliged to act are provincial governments, responsible for assessing the possible loss of life, property and infrastructure.

Pursuant to the Act of 26 April 2007 on Emergency Management (Journal of Laws 2007, No. 89, Item 590, as amended), the transport system is considered critical infrastructure, which determines the measures implemented by the public administration to protect it. These measures include responding to emergencies, addressing their effects, and restoring the pre-disaster state of the infrastructure. The aim is to maintain the functionality and integrity of the transport network (including roads) at all times, both when emergencies occur and in the periods between them. The protection of critical infrastructure includes the collection and processing of data on threats to transport infrastructure, the development and implementation of procedures in the event of a threat, and the restoration of the infrastructure.

The National Programme for the Protection of Critical Infrastructure aims to create the conditions for improving the safety of its subsystems. As regards the road network, it finds it particularly important to introduce a risk assessment protocol that takes into account the occurrence of flooding, including a protocol for dealing with a threat of even remote probability with catastrophic effects. This specific objective requires the identification of those road network elements whose damage would lead to disruption or even a crisis. Authorities engaged in critical infrastructure management are therefore required to draft and implement plans for the protection of critical infrastructure and prepare their own back-up plans and solutions that could substitute for this infrastructure until it is fully restored. The National Programme for the Protection of Critical Infrastructure also emphasises the significant role of scientific institutions and the academic community as a source of knowledge and expertise which can help develop new technologies and analytical methods to assess the risk of damage to or failure of the transport network and to evaluate its susceptibility, an example of which is this monograph.

Measures taken to protect infrastructure should be proportionate to the level of risk – expressed as a function of hazard, susceptibility, and effects. Since it is impossible to affect the level of flood probability, actions taken are aimed at minimising the risk of disruption to the transport network by reducing its susceptibility to flooding and flood-related effects. What seems particularly relevant here is the development of plans for operational continuity and restoration, defined as organisational and technical measures leading to the maintenance and restoration of the vital functions performed by the transport network.

The annex to the National Programme for the Protection of Critical Infrastructure, which stipulates the standards required to ensure the smooth functioning of critical infrastructure, presents good practices and recommendations, and defines the properties of a resilient system: constant accessibility of the services provided, reliability, serviceability, and safety. Thus, the protection measures taken for critical infrastructure should ensure that the high accessibility of road transport infrastructure is maintained at all times. The road network should also be as reliable as possible, which can be achieved through: the mutual substitutability of its components, short repair times (not only when the network is being restored to a minimum acceptable level of functionality but also to its pre-disaster state), constant monitoring (as early as when the first signs of a threat appear), and high quality (here: robustness) of individual components of the network.

Just like any other infrastructure, the road network is subject to gradual deterioration. To ensure that this process does not reduce the robustness of the network against the destructive effects of flooding, it is necessary to maintain its high serviceability. In the event of a flood, it seems particularly important to prepare a plan for the repair work to be conducted. Taking into account the temporal and spatial distribution of flood probability in Poland, repairs should be performed in line with a schedule that minimises the likelihood of co-occurrence of maintenance work and flooding. The safety of critical infrastructure should be achievable by complying with the provisions of both Polish and international laws, norms, standards and guidelines. This monograph, with its modelling of the consequences of potential failures, seems particularly relevant in that matter.

4

THE ROAD NETWORK IN FLOOD HAZARD AREAS

4.1. Identification of sections of the road network within flood hazard areas

Improving the safety of the population and reducing flood-related losses required the identification of flood hazard areas for each flood scenario. Therefore, as part of the IT Country Protection System, flood hazard and flood risk maps were developed with two types of floods in mind – fluvial and coastal (Figure 4.1). Pluvial floods caused by direct rainfall, groundwater, failures of water company infrastructure (water mains, sewage systems, etc.), and hydraulic engineering structures were only analysed in the preliminary flood risk assessment, as in Poland they are considered part of flood risk arising from river and the sea. For this reason, these were not recognised as separate types of floods for which individual flood risk maps were required.

The identification of these areas was possible once the following steps had been taken: a search of the available data sources for emergency response was conducted; a systemic solution to manage it was designed; reference databases were built (data on roads, railways, towns, etc.); and plans identifying possible areas at risk of flooding were drawn up. As a result of these measures, public awareness of the disaster was raised (Maślanka and Wężyk 2014, p. 14). The implementation of the project's findings (through the analytical delineation of flood hazard areas on the basis of long-term modelling) can not only help to mitigate economic losses and improve the effectiveness of the protection of people's lives in Poland (Kurczyński 2014, p. 20), but also to determine specifically which sections of the road network would be flooded in each analysed scenario.

Flood hazard maps and flood risk maps were developed using the results of one-dimensional (1D) and two-dimensional (2D) hydraulic modelling. Both types of modelling are based on a hydraulic approach referred to as the "dynamic wave solution." The approach is described by the full one-dimensional Saint-Venant equations; that is the equation of mass conservation and the equation of momentum conservation (Szwagrzyk et al. 2014, p. 162). In 1D models, a watercourse is simplified to its cross-sectional geometry and longitudinal profile, whereas in 2D modelling the calculations are performed on a grid of elements in a two-dimensional (XY) space. In addition:

A one-dimensional hydraulic model comprises cross-sections of the channel of the modelled watercourse, roughness coefficients of the cross-section points, a diagram of the river network, mapped bridges and bank conditions (flow volumes generated based on hydrological calculations) (Szwagrzyk et al. 2014, p. 163).

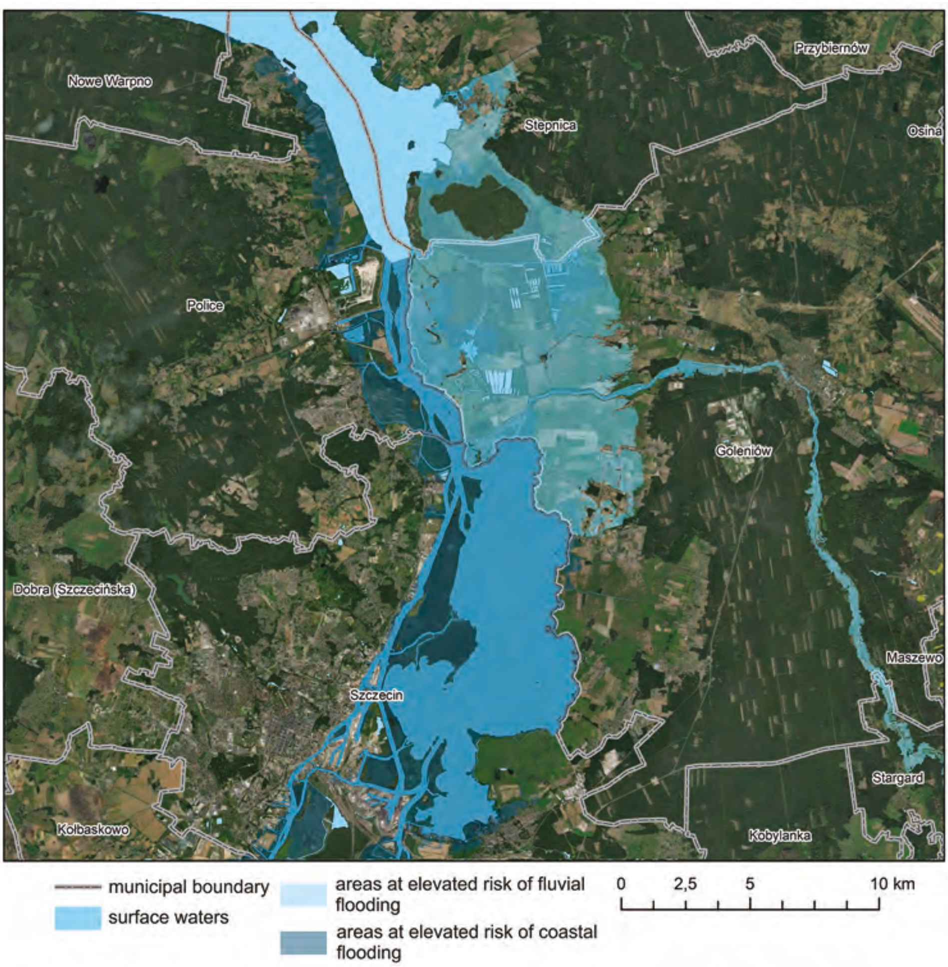

Figure 4.1. An example of the identified areas at risk of fluvial and coastal flooding in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

1D modelling returns data on water table ordinates, water flow volumes and velocities. However, all this data is limited to the modelled cross-sections mentioned above. In order to determine the extent of the flood zone using the results from 1D modelling, it is necessary to interpolate the water table ordinate between the modelled cross-sections and to conduct additional spatial analyses (Szwagrzyk et al. 2014). What proves useful here is the digital terrain model (DTM).[1] The elevation data, which is used primarily to obtain information necessary to describe floodplains and terrain features, includes data on stopbanks, dykes and road or rail embankments, of which the latter two are particularly important for the study described in this monograph (Figure 4.2).

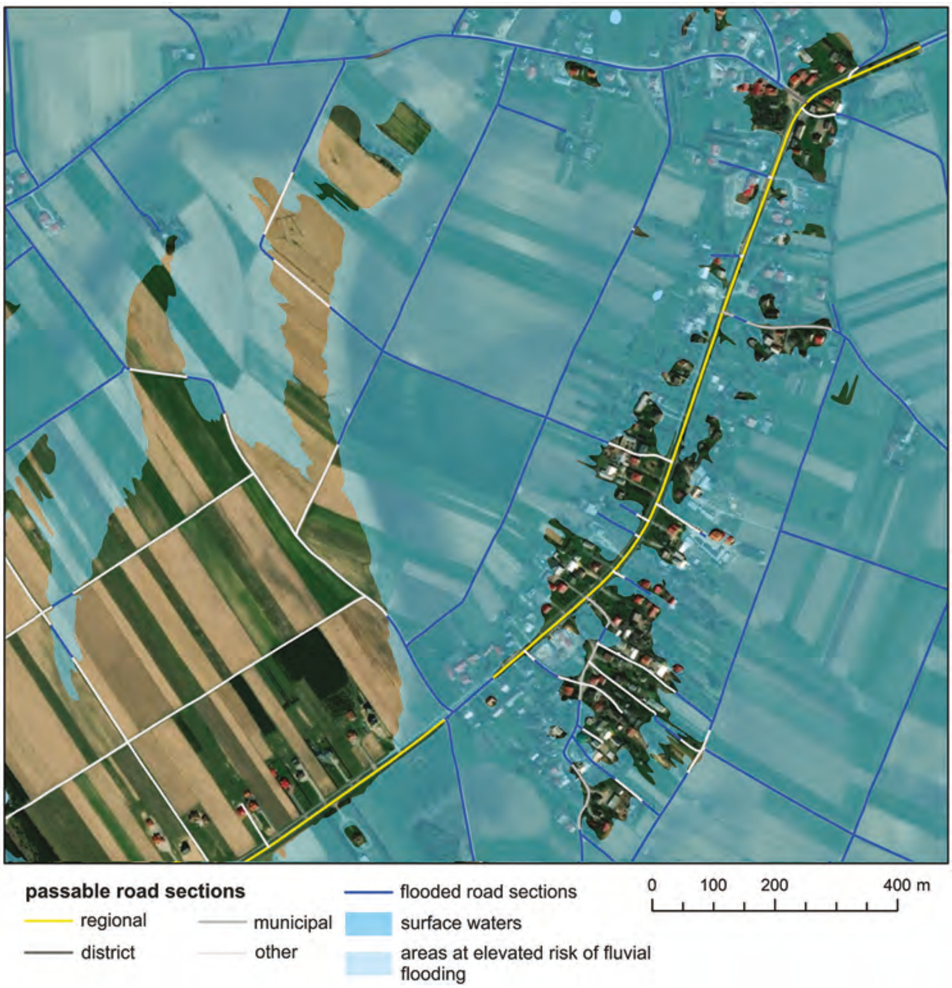

Figure 4.2 An example of a road section running along an embankment and outside the reach of floodwaters in the municipality of Tryńcza (Przeworsk District) in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

[1] "(...) is a structured set of points that represent the topographic heights of the terrain surface, together with interpolation algorithms that allow the reconstruction

Elevation data is applied by those managing the road infrastructure (the General Directorate for National Roads and Motorways, etc.) primarily at the early stages of investment planning (road routing) and for preparing documentation on the environmental impact of the planned investment, where noise and hydrological conditions are modelled. The incorporation of this data in the planning and execution of development optimises the costs of groundworks required for the construction of a given road class, for instance. ALS data also makes it possible to determine: the maximum gradients, obtain information on groundwater levels, and facilitate the assessment of the impact the hydrological conditions may have on planned developments. Access to high-precision elevation data allows a range of analyses to be conducted (including 3D modelling), which optimises the decision-making process for the location of road investments and facilitates the determination of the technical parameters to be met, including grade-separated junctions and road engineering structures. In a publication that illustrates the application of ALS data, the General Directorate for National Roads and Motorways also states that elevation data is the basis for decision-making on the delineation of traffic routes in nature conservation zones, and construction projects planned in areas at elevated risk of waterlogging or susceptible to erosion, scour or mass wasting (Elevation Data to Support the Design and Implementation of Road Investments, General Directorate for National Roads and Motorways).

A detailed inventory of engineering structures on selected watercourses (including bridges, walkways, etc.) was conducted under the surveying work of the IT Country Protection System. First, the precise location of these structures

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(interpolation) of this surface at any location. (...) The simplest data organisation model is based on a grid of squares, where a height (H) is assigned to each node of the grid. In this model, the data can be stored as an array (matrix) and therefore, due to its simplicity and ease of implementation, this model is applied most frequently. In computer software, especially in GIS systems, this model is known as GRID. Its disadvantage, however, is that it cannot accurately reproduce the course of structural lines of the terrain surface, e.g., lines of slope edges. In addition, the GRID model always requires the output LIDAR point cloud to be interpolated to a regular structure (...) A variant of the GRID model is the raster model, where an image (a photo) is generated on the basis of the heights at the grid points, where individual pixels (and thus the area) are assigned the heights of the grid points. Another commonly employed DTM model is based on an irregular triangular grid, which is created from the original ALS data with no interpolation. (...) A solution that combines the advantages of the said two basic DTM models is the hybrid data organisation model, which has a layered structure, where the base layer is a grid of squares with heights (GRID). Subsequent layers can store (as vectors) structural lines of the surface or elements of the triangulated irregular network (TIN)" (Borkowski 2014, pp. 110–111).

was determined. Next, only those that had pillars at least 0.5 metre in width (or diameter), or those with the ordinates of the underside of their structures lower than the level specified by adding 2 metres to the ordinates of the upper edges of the bank slopes (and whose main horizontal structural thickness exceeded 0.5 metre), or had abutments located entirely or partially within the cross-section of the watercourse channel were included (at least one of the above conditions had to be met) (Report on Drawing Flood Hazard Maps and Flood Risk Maps, p. 42). These structures were not included to determine the effects of flooding on the transport network, but because they can affect the flow of water. Nevertheless, they constitute the only data source of such high detail and spatial coverage as regards the impact of floods on road infrastructure.

Other important features from the ALS data are the footprints of buildings and the type of land cover, which helps to determine ground roughness coefficients. The baseline density of a point cloud derived from laser scanning (for Standard I) is 4 points per square metre, which translates into the average distance between points of 0.5 metre, a density that enables the creation of precise DTM models, in which even small natural landforms and important anthropogenic structures such as dykes, slopes or road embankments (which determine geometry of the boundaries of areas at risk of flooding) can be mapped (the minimum density requirement for Standard II is even higher at 12 points per square metre).

2D modelling is performed directly on the grid generated from a DTM model, which allows data on the size and depth of the floodplain to be obtained without additional spatial analysis. 2D modelling allows for data on the velocity and direction of the water flow at each point within the modelled area to be obtained. Unlike 1D modelling, 2D simulations can also be used to analyse those cases where water flows perpendicularly to the normal flow of the watercourse. For this reason, it is employed to simulate scenarios where a stopbank is breached. Unfortunately, 2D modelling requires significantly more time to prepare and conduct, given the considerably greater pool of data and complexity of the model itself when compared to 1D solutions. As a result, under the IT Country Protection System, this modelling was applied only to towns and cities with a population of over 100,000 for which flood hazard maps and flood risk maps were prepared (Szwagrzyk et al. 2014, p. 163).

In order to obtain data on the size of the flood zone and water depth, the ordinates of the water table within the design cross-section must be processed by spatial information systems. According to Szwagrzyk et al. (2014, p. 166):

> A digital water table surface model (DWTSM) is produced using the water table ordinates, which are assigned to the geometry of the cross-section course. Using map algebra, the DTM elevation data is then subtracted from the DWTSM elevation data, thus returning the layer of floodwater depth. On the basis of the

differential model of the surfaces so obtained, the size of the flood zone is calculated and verified using auxiliary data and spatial analyses, which take into account, inter alia, the difference between the water table in the main channel of the watercourse and the water table on the floodplains.

The data on the extent of the flood zone and water depths within its boundaries later helped to determine the magnitude of the flood risk. Once the layers representing the depth of the flood zone and the types of land use therein were taken into account, augmented by the property value attribute of each layer obtained through analyses in GIS software, it was possible to estimate the magnitude of flood losses.

Only areas at low risk of flooding (once in 500 years) are presented on coastal flood hazard maps, including internal sea waters (excluding estuarine river sections) if adequate flood protection is provided. However, on the coastal flood hazard maps generated under the IT Country Protection System, areas where there is a medium probability of flooding (once in 100 years) are also shown, and thus, this scenario was also addressed when changes in accessibility and road network load were analysed. Scenarios where there is a high probability of coastal flooding (once in 10 years) were ignored since adequate flood protection is provided for under these circumstances, mainly owing to the multitude of flood-protection schemes and laws in force in coastal areas of Poland. As a result, during storm surges with a 10% probability of occurrence only beaches (and occasionally the base of dunes) are inundated, while along internal sea waters only those stretches of the shore that are intended to be submerged for ecological reasons are under water. The seashore (including seaports and harbours) is fully protected against coastal flooding with a 5% probability of occurrence along its entire length (Report on Drawing Flood Hazard Maps and Flood Risk Maps, p. 11).

The study also focused on the areas at risk of flooding due to a complete breach of a stopbank; a scenario which identifies a breach in any section of the embankment as the main source of flood risk. This scenario was analysed for all embanked rivers listed in the preliminary flood risk assessment, except where the embankment would be bypassed by floodwaters. In that case, the flood hazard area on the land side of the dyke was addressed as part of the 1% probability flood scenario. The flood hazard area was determined by modelling conducted separately for the left and right land side of the river (i.e., in simulations the embankment on each bank was removed separately). The results of simulations performed for the two banks separately were then merged to determine the total area of possible flood hazard due to a complete breach of the stopbanks (Report on Drawing Flood Hazard Maps and Flood Risk Maps, p. 72). Importantly, the analysis applies to flows for which the probability of overtopping is 1%. Simulations of breaches in dykes located within the areas affected by a storm-surge causing the river to back up were performed for a probability of 1%, the same as for all other embankments. The analysis for areas at risk of coastal flooding and floods caused by sea internal waters applies to water levels for which the probability of overtopping is 1% (Methodology for Preparing Flood Hazard Maps for Areas at Risk of Flooding Due to the Breach of or Damage to Embankments – the Scenario with a Complete Breach of a Stopbank, p. 1).

The processes outlined above generated layers that show the areas inundated by floodwaters for each scenario under the IT Country Protection System. The study presented here addresses those floods with a 10% and a 1% probability (both fluvial and coastal), and floodings due to the total breach of the service strip and stopbanks.[2] When these layers are superimposed on the road network, it is possible to determine which sections would be flooded.

Under the IT Country Protection System, layers were also generated that delimit the boundaries of the areas at risk and illustrate the spatial differentiation of water depths there, which helps to determine the water depth over a given road section. Alas, as water depths were expressed at intervals (the first up to 50 cm), it is impossible to determine the exact water depth. Therefore, it was assumed that if the floodwater covers a given road section, this section would be considered closed to vehicle traffic. To date, a number of studies have been conducted on the correlation between the depth of standing floodwater on a given road and its passability. For instance, Liu et al. (2016) suggested that road use was possible at depths of up to 30 cm, however, they indicated that travelling under such conditions involves a drastic decrease in speed and a significant increase in the probability of vehicle breakdowns, collisions and accidents. The high risk when travelling along a section of the road network where standing water appears even at the shallowest depth is also stressed by Gissing et al. (2019), who argue that in such circumstances the section in question should be closed. Due to the lack of accurate data on water depths, a given section should therefore be closed for the sake of users' safety even if initially the authorities decide not to close it preventively.

Here, it must be emphasised how important it is to be extremely precise in mapping the road sections running in the vicinity of watercourses within the road network model (e.g., the linear layer representing the road section must be identified as running along the embankment and not next to it). Insufficient precision can result in a situation where a given section is included within the flood hazard areas, even though there is an embankment which raises it above

[2] Areas where there is a 1% probability of flooding are also included in this scenario, since the flood-related breach of the embankment cannot occur without the presence of water in the inter-embankment zone.

the level of floodwater in reality. Therefore, when building the road network model, the data contained in the flood hazard and flood risk maps on the course of roads was taken into account. Obviously, a section may still be closed if there is a risk of the road embankment becoming unstable even before the floodwater has reached the road surface. However, such decisions should always be on a case-by-case basis, preceded by real time and long-term observations.

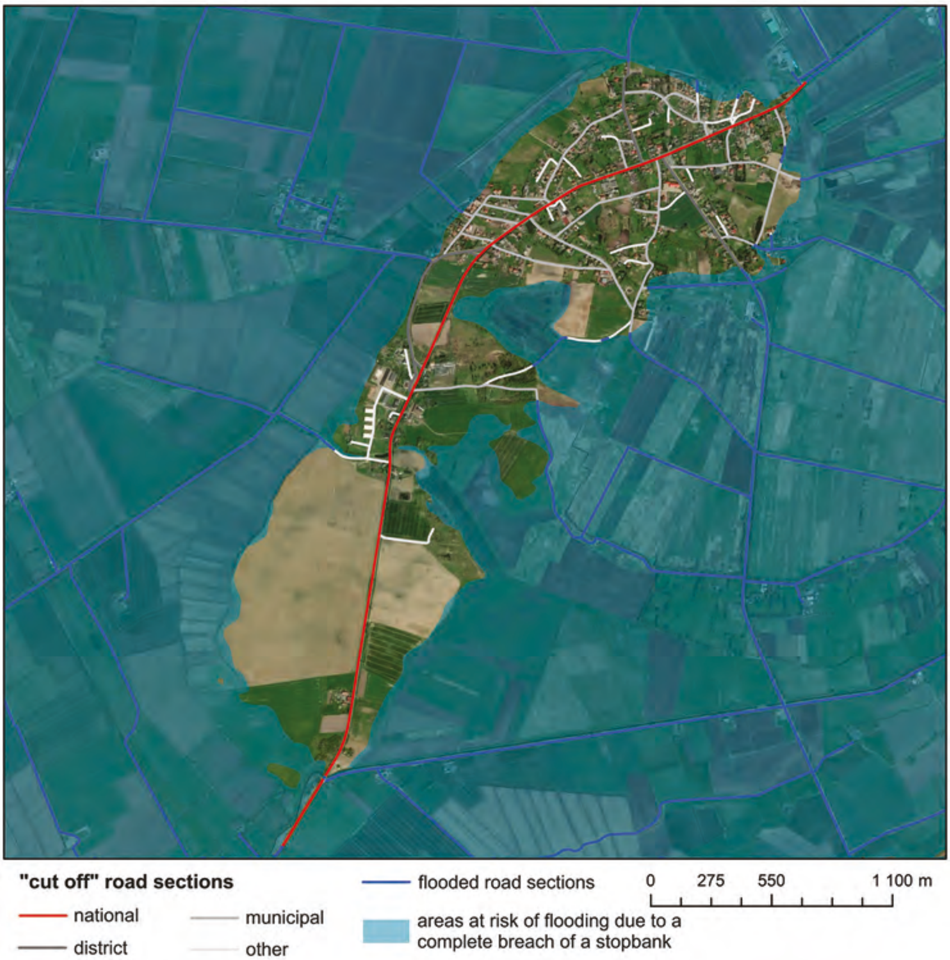

Figure 4.3. An example of a road section "cut off" when neighbouring sections are inundated in the municipality of Gronowo Elbląskie (Elbląg District) in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019)

On the basis of the layers that represented the road network and flood hazard areas in the scenarios analysed, flooded sections within individual water regions were identified. This procedure also revealed sections which, although not flooded, were still excluded from use, i.e., road sections "cut off" when other, neighbouring sections, were inundated (Figure 4.3). Although indirectly, these "cut-off" road segments still expand the list of sections affected by flood, as they might further reduce accessibility and increase the load on other sections of the network.

4.2. Methodology for verifying the safety of road engineering structures and new developments in road infrastructure

The modelling outlined in Subchapter 4.1 used the elevation data from a DTM model produced on the basis of data collected in different parts of the country between the final quarter of 2010 and late 2015. As for the research objectives adopted in this monograph, there were two issues that needed addressing. Firstly, it was necessary to identify elements of the road network (e.g., those running along embankments) that were constructed or upgraded after the airborne laser scanning of a given area had been completed, which meant that they had not been included in the original modelling. Secondly, the safety of road engineering structures had to be verified, since those included in the modelling had only been selected for their possible impact on water flow capacity, not the safety of these structures themselves. Determining the vulnerability of a given structure (here: a road engineering structure) is a complex task, as it requires a number of factors to be considered; factors that can determine whether a given structure would be damaged or destroyed (Marcinkowski 2006, Pregnolato, Sarhosis and Kilsby 2018, Pregnolato 2019, Yuan et al. 2019).

Newly built or upgraded[3] road sections are assumed to possess technical specifications in line with specific road classes and traffic categories. However, parts of the road network were designed and built without taking these regulations into account, and thus, they require additional verification. Highly valuable data on the properties of individual road sections can be obtained from highway management authorities, as they are obliged to keep records,[4] which is useful for collating and understanding data on public roads, etc. (Marcinkowski 2006).

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[3] Execution of roadworks resulting in an upgrade of the technical and operational parameters of an existing road that do not require a change in the boundaries of the existing footprint of the road (Act of 21 March 1985 on Public Roads, Journal of Laws 1985, No. 14, Item 60, as amended).

[4] Road operation logs, road inspection logs, list of roads, and technical and operational maps.

The factor that determined whether a given road section which was under construction during ALS scanning was included in the modelling was its presence in the reference layer representing the road network. If a given section was identified there, it was assumed that the hydrodynamic modelling indicated whether it would be flooded during a given flood scenario. If the section was built later, it was, for obvious reasons, deemed as being absent in the modelling, although it was still necessary to determine whether it would be inundated under the various flood scenarios. Taking into account the principles and practices for the construction and operation of road infrastructure (as outlined in Subchapter 3.4), it was assumed that new road infrastructure within areas where there was a 1% probability of flooding would not be inundated in any scenario.

As regards developments in road infrastructure outside areas at elevated risk of flooding, it was assumed that only the newly built motorways and expressways (key road developments) are "robust" to floodwaters. It was also deemed that other roads in areas at risk of flooding due to a complete breach of the service strip or stopbanks would be flooded. Another issue to be addressed was modifications to road sections (e.g., construction of a road embankment), which could change their elevation, thereby affecting their susceptibility to flooding. Since upgrading does not alter the existing footprint of the road, it is invisible in the layer representing a given road section. To this end, it was necessary to verify that the scanning was performed after the upgrading process had been completed and that its possible impact on the ordinate of the road was thus captured. For this purpose, data from highway management authorities was obtained. Namely, data on road investments was retrieved from the General Directorate for National Roads and Motorways, more precisely from the Programme for the Construction of National Roads for the Years 2014–2023 (with proposals up to 2025), which the Directorate is currently following while implementing investments in national roads. Data on investment projects for the existing road network that are related to the expansion and upgrading of road sections, the improvement of road traffic conditions, safety, and traffic management systems were also accessed. Information from the highway management authorities of individual regions was also used regarding investments implemented within: the framework of the Integrated Regional Operational Programme; the Province Regional Operational Programme; the Operational Programme for Development of Eastern Poland; subvention funds for co-financing investments on local roads, funds from the Ministry of Infrastructure and Development; subvention funds of the Ministry of Infrastructure and Construction, and funds provided by individual provinces. Regional governments provided data on investments implemented under the National Programme for Redevelopment of Local Roads (2008–2011, Stage II – Safety, Accessibility, Development); the Government Programme for the Development and Competitiveness of Regions through Improvement of Local Road Infrastructure; the Programme for Development of Municipal and District Road Infrastructure in 2016–2019; the European Union Solidarity Fund (emergency measures taken to overcome the effects of floods in May and June 2010, initiated in order to restore municipal infrastructure to its pre-flood state as quickly as possible); and funds from the state budget allocated to alleviate the effects of landslides or other effects of natural disasters. Whenever it was necessary to verify whether a given section of a district or local (municipal) road had been built, or if its important parameters had changed after the data for the production of the DTM model had been gathered, and the section was not listed in the aforementioned datasets, the appropriate authority or municipality office was contacted.

The data thus extracted was "superimposed" on the DTM index, where each sheet was assigned its up-to-datedness. If the date of completing a given development was not later than the data listed in the DTM index, it was assumed that it was captured in the hydraulic modelling. If, on the other hand, a given new road infrastructure was completed later, the descriptions of listed developments were analysed first. Given the huge volume of the data, it was impossible to obtain detailed documentation for individual items of the lists. If the description indicated that the new road infrastructure did not affect important technical and operational parameters (e.g., only the road markings were changed to improve road safety), it was assumed that such an upgrade did not impact the susceptibility of the section to flooding. One should bear in mind that data on road developments is not uniform and varies greatly in detail. In other cases, where the new road infrastructure was located in an area at elevated risk of flooding, it was considered to have contributed to reducing the susceptibility of the section to flooding. For investments outside areas at elevated risk, the same principle was adopted as for road sections under construction. Although the incorporation of documentation from road infrastructure bodies involves certain risks (arising from, amongst others, the somewhat subjective descriptions of road investment projects), it still represents an acceptable compromise between processing the most detailed spectrum of data and the available time for its analysis.

As road engineering structures (bridges in particular) are key elements of the road infrastructure, affecting the parameters of a given road, determining the permissible weights and dimensions of vehicles that can travel along a given section, and conditioning the number of vehicles that can pass over the structure (Marcinkowski 2006), it was considered crucial to assess the susceptibility of these structures to inundation by floodwaters. To this end, the following procedure was applied. Firstly, it was determined whether a given structure was in place at the time of scanning, i.e., whether it was present in the reference layer of the road network. If so, it was possible to verify the ordinate of its surface using the Digital Surface Model (DSM) (Figure 4.4).

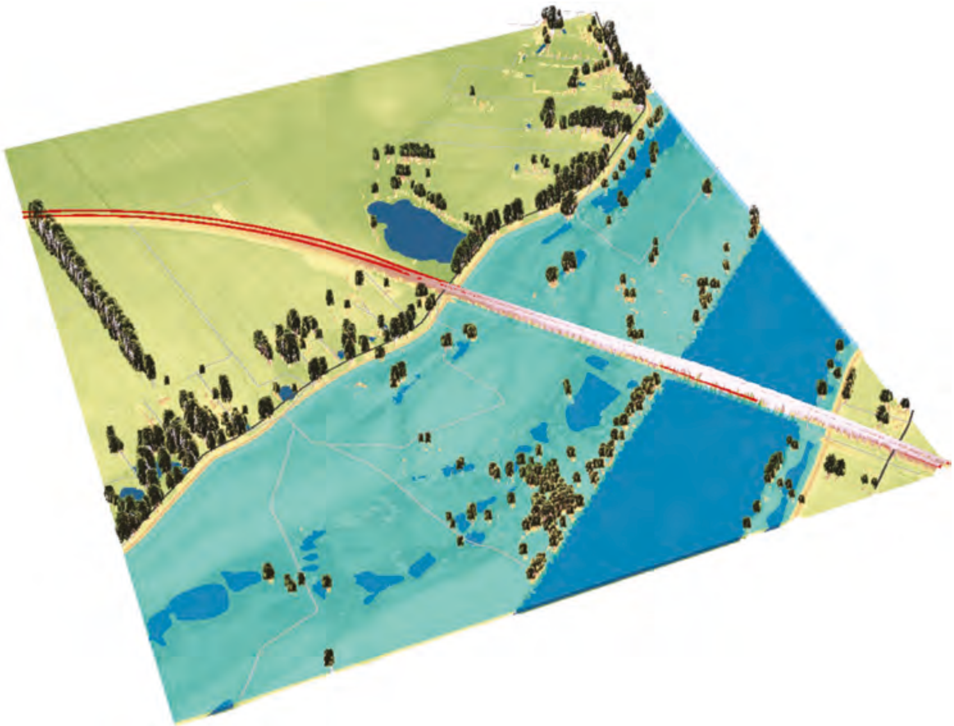


Figure 4.4. DSM data visualisation showing a bridge over the Vistula along the A1 motorway near Grudziądz in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Digital Surface Model by the Head Office of Land Surveying and Cartography (2019)

A DSM model is an image of the surface of the terrain (land) further extended with data that maps land use items considered a permanent part of the surface (vegetation, buildings, technical infrastructure, etc.). Here, a fundamental difference between DSM and DTM models is revealed; in the latter, measurement errors are filtered out so that the final product is a smoothed surface. However, a DSM model allows objects with clearly discernible edges (buildings, engineering structures, etc.) to be mapped. Although it usually has the form of a GRID network, it can also be a triangulated irregular network (TIN). According to Borkowski (2014, p. 126):

> A DSM model generated from ALS data shows greater non-homogeneity in the distribution of errors for individual land cover classes than a DTM model. Two sub-areas can be distinguished within the area covered by a DSM

model, one being the land free of any objects and vegetation. In these areas, a DSM model overlaps with a DTM model and the accuracy of both should be the same; any discrepancies may only stem from different interpolation methods. In other areas where objects of land cover are present, a DSM model will be less accurate than a DTM model. The largest differences between the actual height of an object and the height shown by a DSM model will arise for such objects as tree crowns or building edges. In a DSM model, the edges (walls) of buildings will be eroded and for these spots errors in a DSM model can be up to several metres, thus – when acquiring elevations (both of terrain and objects) from a DSM model – it is imperative to place measurement points away from the edges of such objects.

This recommendation was followed when the procedure outlined below was applied. Firstly, survey points located within 1 metre of one another were generated along the line representing a given engineering structure, running along its longitudinal axis; and each point was then assigned geographical coordinates. Next, a search was initiated through the DSM text database that contained the coordinates of the points arranged into a regular grid with an edge length of 0.5 metre for urban areas (Standard II) or 1 metre for other areas (Standard I), and the absolute elevation assigned to them. The average elevation error did not exceed 0.2 metre. The search was conducted to identify the points in the DSM database nearest to the survey points on the axis of the structure in question. As a result, a set of points no more than 1 metre away from its axis was obtained for each structure, thus showing the ordinate of its surface. Next, it was also necessary to determine the maximum ordinate of the water table in each flood scenario, using layers of flood hazard maps that contained points to which values of the ordinate of the water table for each flood scenario were assigned based on hydraulic modelling. Once the points representing the ordinates of the structure's surface and the ordinates of the water table were combined, it was possible to indicate whether any section of the structure was at risk of flooding and to determine the clearance between its surface and the water table (Figure 4.5).

If any section was considered to be flooded under any flood scenario, it was excluded from the network in the simulations for that particular scenario. For structures that were not mapped in the DSM model (having been built or upgraded later), it was assumed that the construction regulations presented in Subchapter 3.4 were applied and these structures were deemed robust against a 1% probability flood.

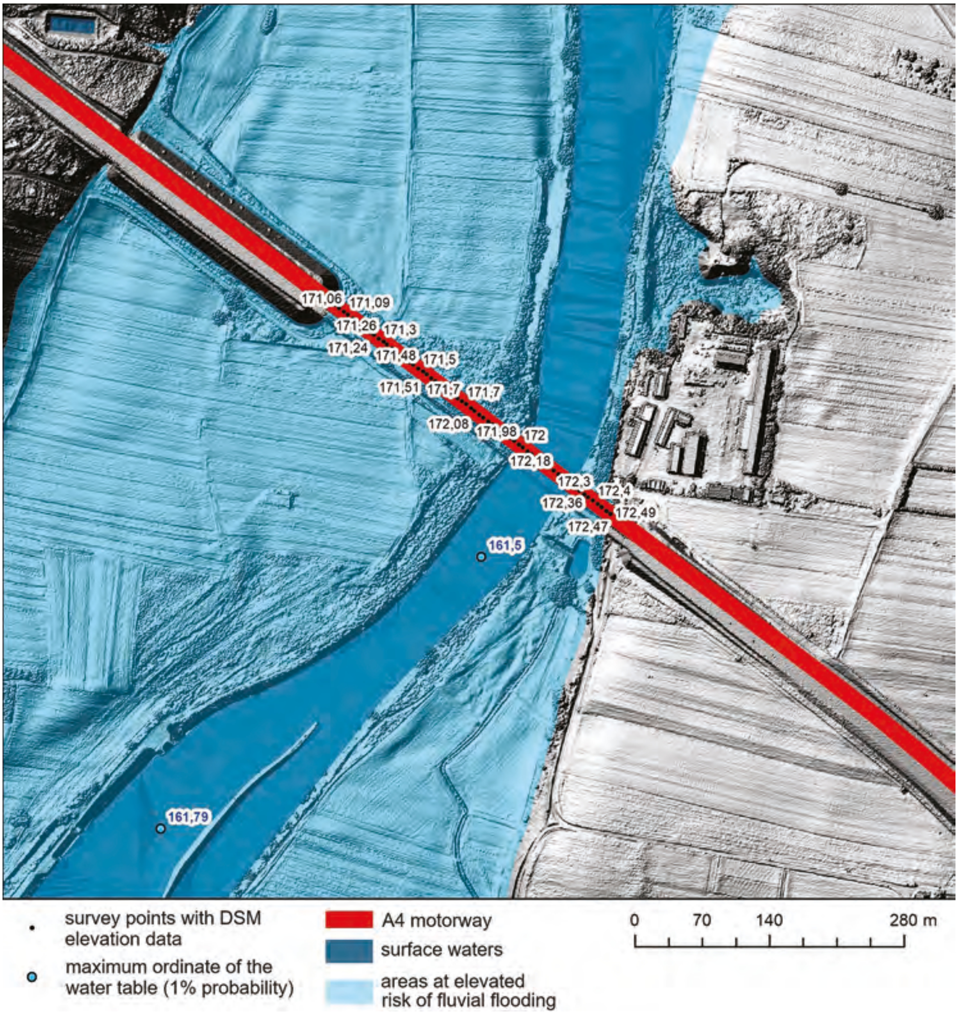


Figure 4.5. An illustrative juxtaposition of DSM data and the maximum ordinate of the water table (a bridge over the Oder along the A4 motorway) in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Digital Surface Model by the Head Office of Land Surveying and Cartography (2019)

When assessing the vulnerability of engineering structures to damage, their structural specifications must obviously be considered. The cross-sections and structural components where the highest internal forces (bending moments) occur are the most vulnerable. The larger the structure (i.e., the more complex its design and cross-sections, and the more unique its construction technology), the more likely it is to be damaged or destroyed (Marcinkowski 2006). Given the fact that they must be precisely suited to local conditions, road engineering structures (such as bridges) need to have a high-spec design, which usually requires site-specific technical solutions to be applied, thereby making it hard to adopt a single universal method for their examination. In addition, damage to road engineering structures can be complete, partial or only a restriction on how the road is used, which means there is a wide spectrum of possible damage scenarios (Marcinkowski 2009). The methodology applied here for verifying the robustness of engineering structures to flooding does not take into account the detailed spectrum of technical specifications of their construction, which arguably poses a limitation (and a possible path for further research). It is, however, a relatively objective approach that allows massive databases to be reviewed and verified within an acceptable period and with the computational capacity available.

4.3. Location of sections of the road network at risk of flooding

The methodologies described in Subchapters 4.1 and 4.2 made it possible to identify those road sections which would be flooded (or "cut off" from the road network due to inundation of neighbouring sections) in a given scenario. In the flood scenarios considered, the following regularity becomes evident: the longer the cumulative length of the flooded sections, the lower the road category, which is concordant with the general structure (by road category) of the road network in Poland. The only deviation is observed for floods due to a breach of the structure of the service strip, where the length of flooded sections of national roads is greater than that of regional roads, and the length of flooded sections of district roads exceeds that of municipal roads. The closest resemblance between the structure of the length of flooded sections and the general structure of the road network is observed in the scenario where a stopbank is breached (deviations do not exceed 2 percentage points). This scenario is also by far the most dangerous for the road network in absolute terms.

As regards the "cut-off" road sections, deviations from the above regularity (where the percentage of roads of lower category roads dominates over those of a higher category) are also observed in the scenario where there is a flood of high probability due to a breach of a stopbank, and where there occurs a coastal flooding of medium probability. Then, the length of affected sections of national roads is greater than that of regional roads. As for the scenario in which the structure of the service strip is breached, this is exacerbated even further. The same scenario also brings the greatest deviations from the general structure (by road category) of the road length in the country. Then, the percentage of roads classed as "other" decreases by almost 30 percentage points, with an increase of almost 19 percentage points for national roads and over 11 percentage points for district roads. In absolute terms, a fluvial flood with a 1% probability contributes to "cutting off" the longest cumulative road network. As regards the ratio between the lengths of the inundated and "cut-off" sections, the predominance of the latter (107.44%) is only observed in the scenario where there is a coastal flood of medium probability. In all other scenarios, the percentage ranges from around 5% to approximately 30%. When the analysis focuses on the percentage of separate road categories, the prevalence of "cut-off" lengths is particularly noticeable for national roads (over three times greater) and district roads (over two times greater) in the 1% C scenario (Figure 4.6).

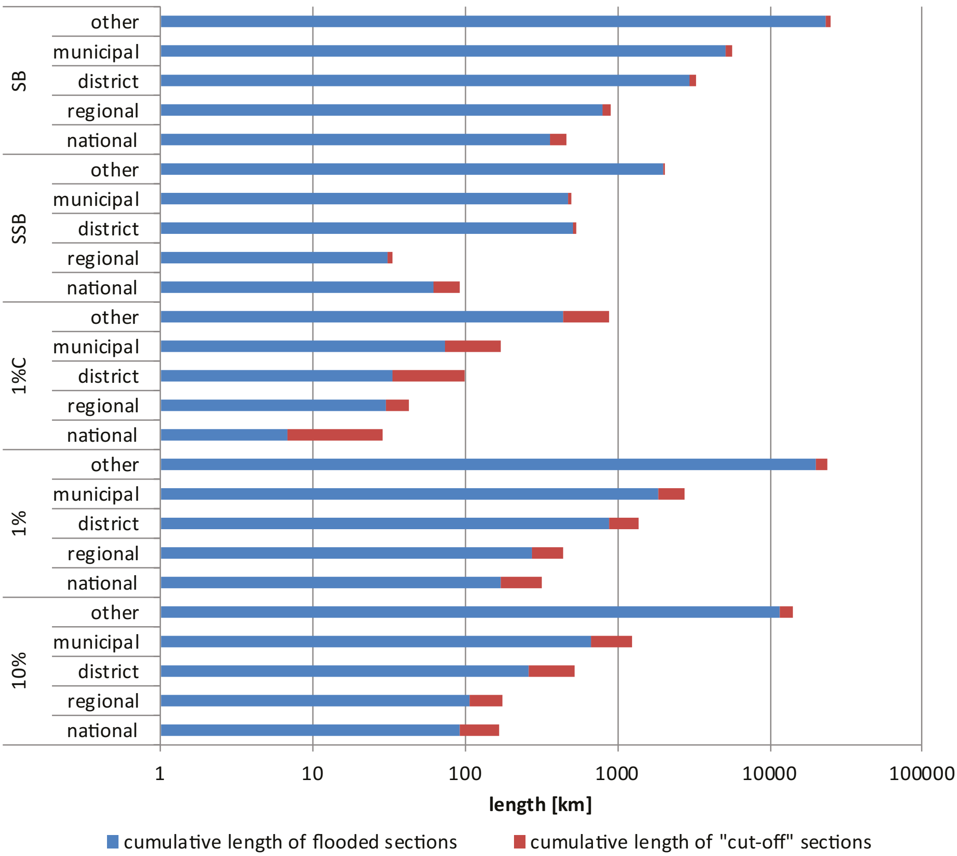


Figure 4.6. Cumulative lengths of flooded and "cut-off" sections of the road network by road category and by flood scenario in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

Table 4.1. The percentages of flooded and "cut-off" sections within the road network by road category, flood scenario and location in 2019 [%]

Water region	sections	Flood scenario																								
		10%					1%					1%C					SSB					SB				
		road category																								
		national	regional	district	municipal	other	national	regional	district	municipal	other	national	regional	district	municipal	other	national	regional	district	municipal	other	national	regional	district	municipal	other
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
the Bug	flooded	2.30	2.15	5.19	8.58	9.91	1.55	2.51	4.26	6.33	8.66	–	–	–	–	–	–	–	–	–	–	0.10	0.13	1.08	0.92	2.28
	"cut-off"	1.42	3.35	6.21	3.07	2.03	1.29	1.66	2.66	2.00	0.91	–	–	–	–	–	–	–	–	–	–	1.24	0.03	0.38	0.38	0.71
the Lower Vistula	flooded	9.67	6.94	1.67	3.41	4.55	6.12	3.83	1.59	3.88	3.45	9.08	54.31	21.40	28.43	28.56	67.16	84.33	90.36	93.07	84.67	30.32	15.59	23.52	20.14	15.78
	"cut-off"	16.54	1.84	1.44	6.00	0.95	10.09	1.20	0.79	3.31	0.79	12.88	19.81	53.78	38.67	33.94	32.17	6.94	5.63	3.59	2.71	6.86	0.22	1.96	1.16	0.52
the Upper Eastern Vistula	flooded	4.44	2.84	7.46	4.72	8.48	8.89	5.34	12.48	8.86	11.77	–	–	–	–	–	–	–	–	–	–	3.95	4.93	3.84	4.74	5.85
	"cut-off"	0.21	1.23	1.85	0.81	0.96	3.53	5.60	5.35	3.01	2.17	–	–	–	–	–	–	–	–	–	–	2.37	1.29	0.65	0.49	0.31
the Upper Western Vistula	flooded	8.47	10.60	8.97	9.49	10.45	8.42	8.29	7.61	8.86	8.47	–	–	–	–	–	–	–	–	–	–	15.34	22.64	26.92	28.48	22.24
	"cut-off"	0.32	0.83	1.79	1.25	0.39	0.50	0.85	0.50	0.51	0.20	–	–	–	–	–	–	–	–	–	–	2.81	3.07	2.16	1.49	1.32
the Little Vistula	flooded	0.63	0.33	0.53	0.28	0.62	1.49	0.55	0.99	1.40	0.84	–	–	–	–	–	–	–	–	–	–	3.04	0.27	1.03	1.89	1.51
	"cut-off"	0.39	0.47	0.00	0.03	0.01	3.39	0.45	0.23	0.34	0.10	–	–	–	–	–	–	–	–	–	–	0.00	0.69	0.30	0.28	0.09
the Narew	flooded	1.24	0.52	0.64	1.45	4.99	0.92	0.49	1.97	3.17	5.28	–	–	–	–	–	–	–	–	–	–	0.28	0.00	0.17	0.28	0.27
	"cut-off"	0.50	0.00	0.60	0.77	1.04	0.79	0.24	2.56	0.91	0.89	–	–	–	–	–	–	–	–	–	–	0.04	0.00	0.01	0.02	0.00
the Middle Vistula	flooded	11.09	12.72	6.25	7.61	12.03	7.81	10.67	8.11	9.99	11.94	–	–	–	–	–	–	–	–	–	–	15.23	22.09	14.18	16.85	16.78
	"cut-off"	3.60	5.71	3.23	2.63	2.45	7.03	5.54	3.90	3.27	2.18	–	–	–	–	–	–	–	–	–	–	3.34	1.75	0.86	0.86	0.68
the Lower Oder and the coastal strip of West Pomerania	flooded	0.87	3.75	0.63	0.41	1.89	0.58	3.05	0.73	0.40	1.44	14.50	16.16	11.53	14.75	22.07	0.29	6.79	3.91	3.28	12.08	0.00	1.42	0.27	0.03	0.92
	"cut-off"	1.50	5.43	1.53	0.70	0.55	0.79	2.27	0.74	0.36	0.31	63.53	9.72	13.30	18.15	15.43	0.38	1.93	0.10	0.05	0.55	0.00	0.59	0.00	0.00	0.13
the Upper Oder	flooded	1.92	4.08	2.73	2.92	2.94	3.99	7.36	4.20	4.97	4.28	–	–	–	–	–	–	–	–	–	–	1.52	3.18	1.16	1.81	1.70
	"cut-off"	1.01	5.40	3.13	3.95	0.99	1.70	2.11	1.53	1.94	0.61	–	–	–	–	–	–	–	–	–	–	0.53	0.08	0.15	0.07	0.04

Tab. 4.1 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
the Noteć	flooded	0.30	1.39	0.32	0.19	1.67	0.18	0.89	0.21	0.28	1.87	–	–	–	–	–	–	–	–	–	–	0.00	0.01	0.30	0.12	0.91
	"cut-off"	1.03	3.65	6.00	3.82	2.78	0.54	2.38	2.43	2.04	1.72	–	–	–	–	–	–	–	–	–	–	0.00	0.01	0.33	0.03	0.16
the Middle Older	flooded	6.94	11.66	11.71	8.52	14.05	9.50	18.10	18.04	13.49	17.45	–	–	–	–	–	–	–	–	–	–	6.81	17.64	10.06	9.79	16.09
	"cut-off"	11.34	7.81	13.41	10.00	3.73	11.25	6.37	9.01	6.23	3.05	–	–	–	–	–	–	–	–	–	–	2.16	3.06	1.58	1.14	2.01
the Warta	flooded	6.49	3.18	3.61	6.17	9.48	3.73	1.78	2.92	6.28	8.48	–	–	–	–	–	–	–	–	–	–	3.86	1.05	7.53	7.44	8.89
	"cut-off"	7.38	3.97	11.01	13.04	3.04	5.68	8.41	7.13	8.03	3.13	–	–	–	–	–	–	–	–	–	–	0.21	0.26	1.56	1.59	0.78
the Łyna and the Węgorapa	flooded	0.10	0.04	0.10	0.05	0.01	0.06	0.02	0.07	0.05	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	"cut-off"	0.32	0.11	0.02	0.16	0.01	0.17	0.04	0.00	0.07	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects.

The incorporation of spatial differentiation into the analysis (Table 4.1) makes it possible to indicate in which water regions a flood of a certain probability would be particularly severe for the road network. As regards floods with a high probability of occurrence, it is the water region of the Lower Vistula, where over 25% of total length of national roads for the affected location in this scenario would be excluded from use (flooded or "cut off"). In the scenario where there is a flood with a 10% probability, the water regions of the Middle Vistula, the Middle Oder, and the Warta would also suffer major disruptions to road transport. In this case, the structure of excluded road sections (by road category) against the whole road network at risk is more balanced. The situation is similar in the scenario where there is a fluvial flood of medium probability. However, it is the road network in the water region of the Middle Oder that is most at risk then, and this applies to all road categories there. As for the scenarios where there is a coastal flood, the risk for road transport is noticeably higher in the basin of the Vistula. The only exceptions are for national roads, which would also be "cut off" in the water region of the Lower Oder and the coastal strip of West Pomerania due to the inundation of neighbouring sections of the network. The scenario in which a stopbank is breached poses the greatest threat to the road network in the water regions of the Lower Vistula and the Upper Western Vistula. As regards national roads in the water region of the Lower Vistula, over 33% of all sections at risk could be flooded or "cut off" in this scenario.

The analysis conducted on a municipal scale revealed how severely flooding could affect road transport locally under the different scenarios, and exposed those areas where the country's whole road network is particularly vulnerable to this type of hazard. In the event of a flood with a high probability of occurrence, nearly 25% of the total length of roads in the affected municipalities could be inundated. In this scenario, the most vulnerable municipalities are found in Silesia (on average 1.74% of the total length of the road network of municipalities affected would be flooded), Subcarpathia (2.76%), Lesser Poland (2.88%), and Masovia (2.30%) (Figure 4.7). Considerable lengths of the road network are also at risk of flooding in large cities (Warsaw, Kraków, Poznań, etc.), but given the high density of the road infrastructure there, the sections at risk rarely account for more than 2% of the total network. With an average of 1.95% for the entire set of such municipalities where any road inundation has occurred, this average deviates by 2.86 percentage points.

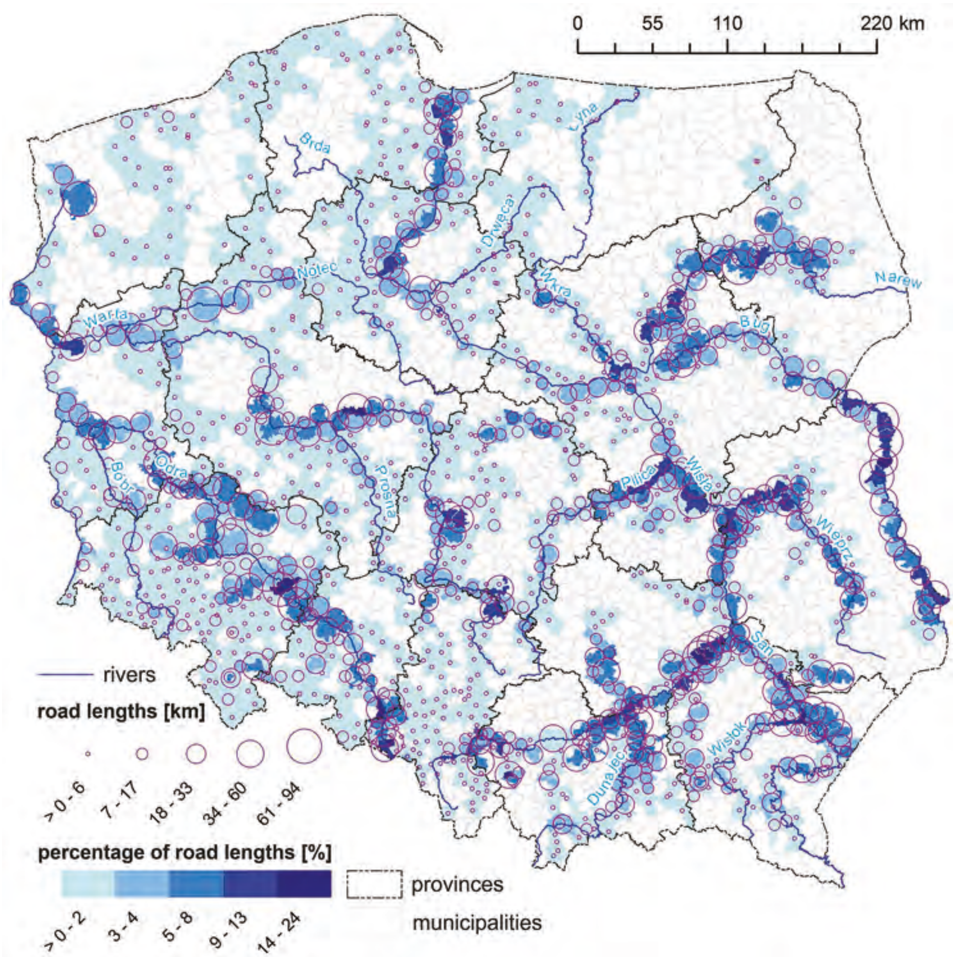


Figure 4.7. The length of flooded road sections and their percentage against the total length of roads in municipalities in the event of a flood with a 10% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

In the scenario where there is a fluvial flood with a 1% probability of occurrence, the maximum increase in the length of the network at risk of flooding for individual municipalities is revealed to be more than twice as great as in the scenario with a flood of high probability. This is discernible both in absolute terms and in the percentage of the inundated road sections against the entire road network per municipality. Particularly noticeable increases are observed in municipalities in Lower Silesian Province and Opole Province (Figure 4.8). The average percentage of the length of flooded roads against the total length of the road network in municipalities where flooding occurs is approximately 1.6 percentage points higher in the scenario where there is a 1% probability flood compared to the scenario where there is a 10% probability flood. However, its variability is almost twice as high.

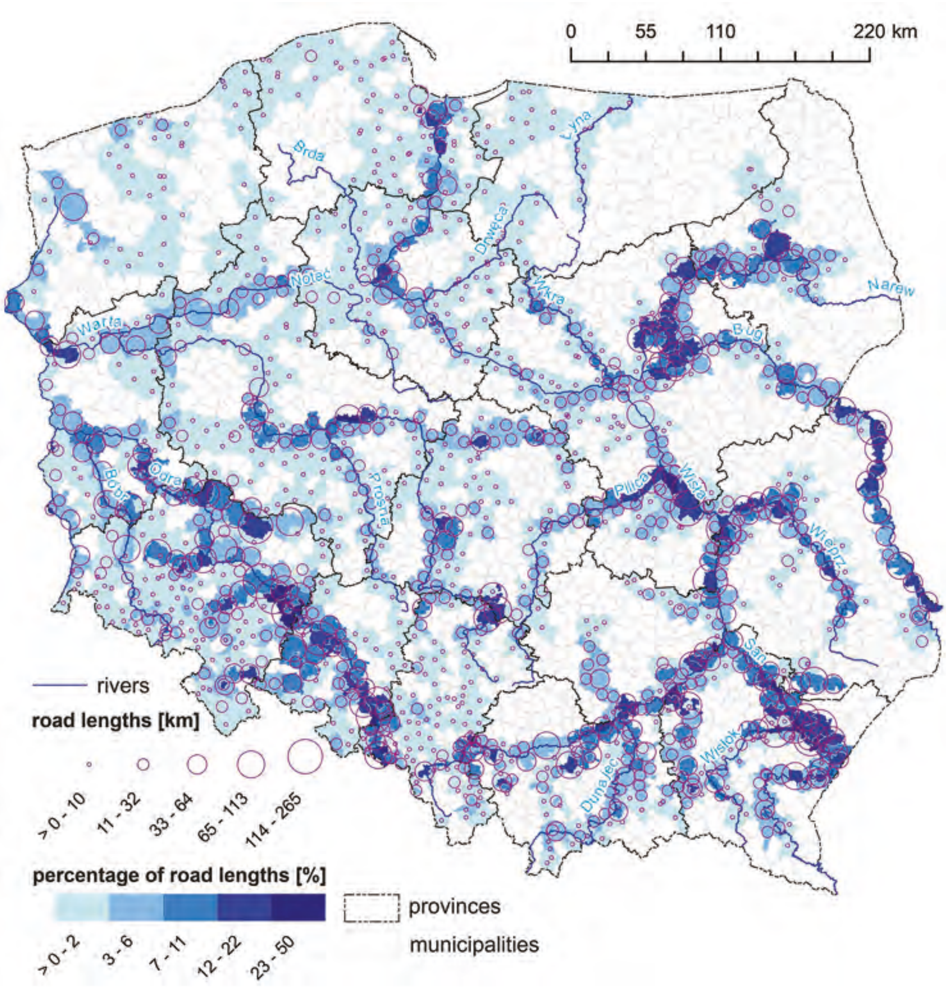


Figure 4.8. The length of flooded road sections and their percentage against the total length of roads in municipalities in the event of a fluvial flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

A coastal flood of medium probability would inundate a considerably smaller length of the road network, which would not exceed 10% of the total network in the majority of affected municipalities. One exception are municipalities on the Hel Peninsula, where up to 50% of the road network may be impacted in this scenario (Figure 4.9).

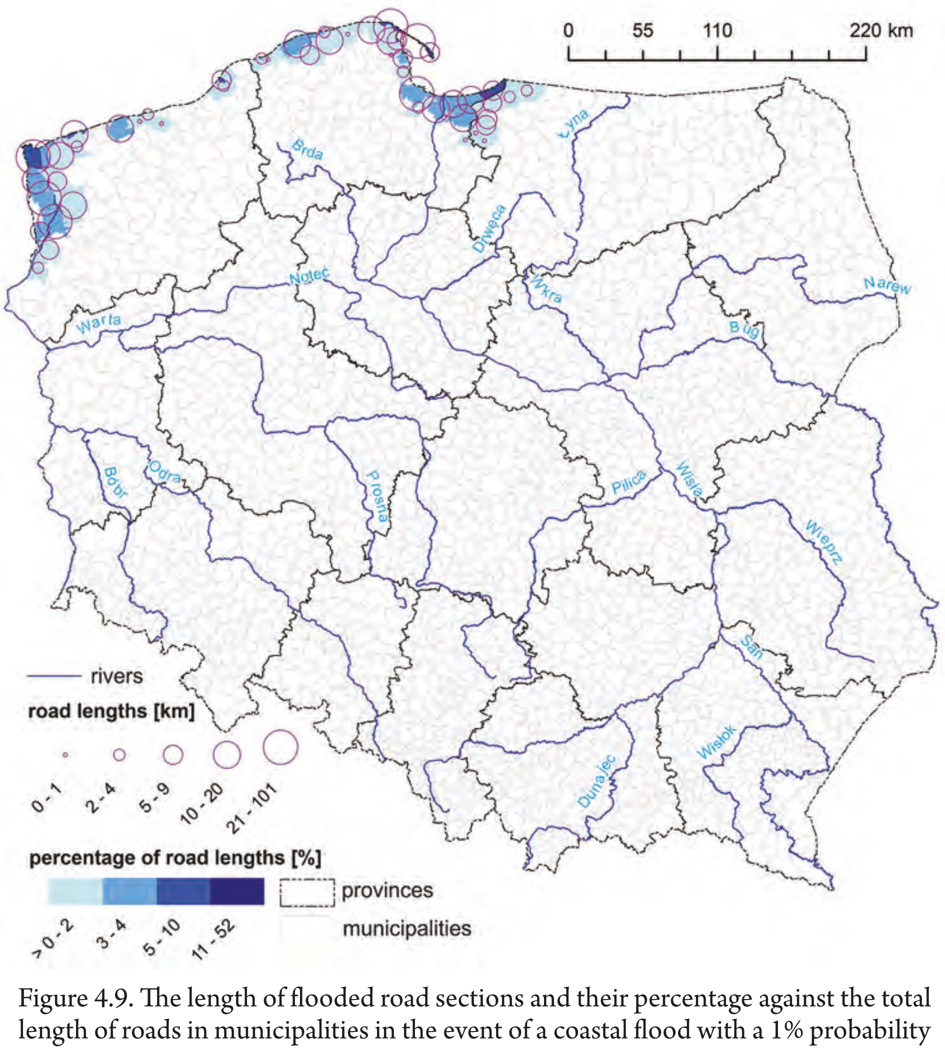


Figure 4.9. The length of flooded road sections and their percentage against the total length of roads in municipalities in the event of a coastal flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

The situation is considerably worse when the protective structure of the service strip is completely breached, where as much as 90% of the road network within the municipalities located in the Vistula Fens would be flooded. However, this is a scenario where the extensive road network exclusions affect the smallest group of municipalities (Figure 4.10).

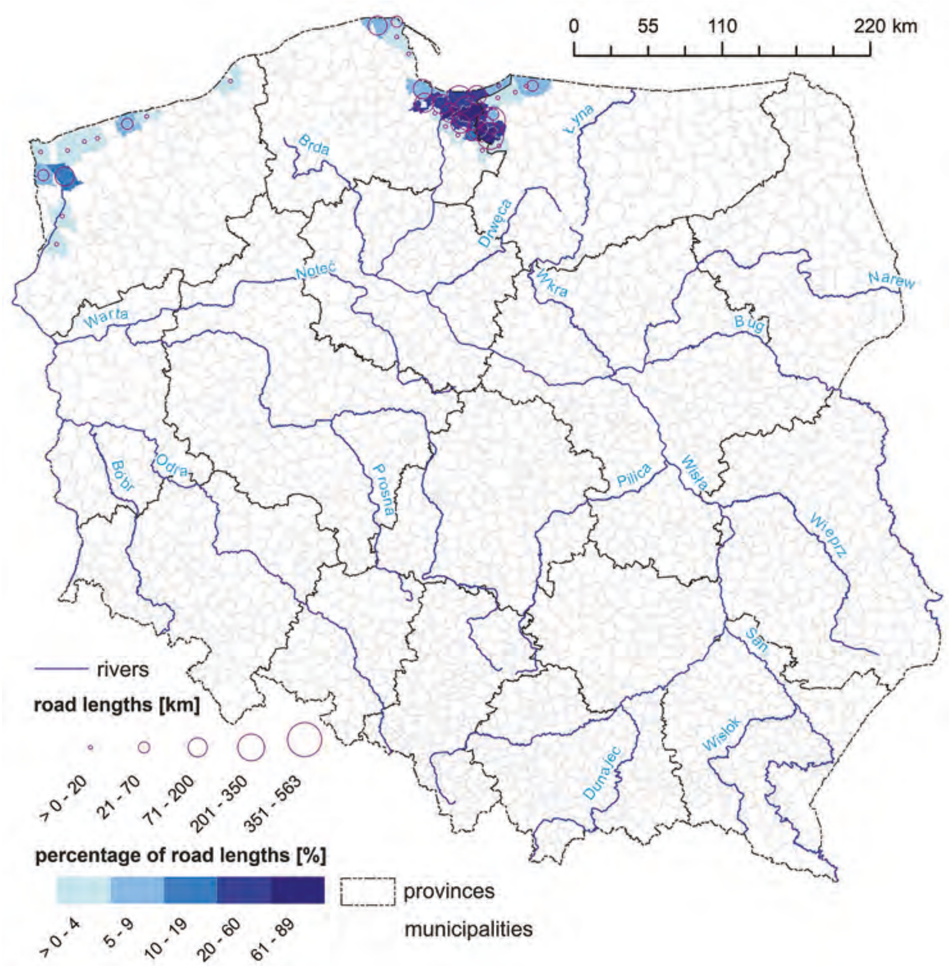


Figure 4.10. The length of flooded road sections and their percentage against the total length of roads in municipalities in the event of a flood due to a complete breach of the protective structure of the service strip in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

The greatest threat arises from a complete breach of stopbanks, as in this scenario there are municipalities where almost the entire road network would be inundated (again, this applies to the delta plain of the Vistula). Regions where the situation would not be as serious, but still severe, are Warmia-Masuria, Świętokrzyskie, Subcarpathia, and Lesser Poland (the average among the municipalities does not drop below 20% there). The prognoses are clearly worse for municipalities in the basin of the Vistula (Figure 4.11), where on average 17.79% of the municipal road network would be flooded (for municipalities where any flooding of the network occurs). In the basin of the Oder, the average is as much as 10.97 percentage points smaller and the standard deviation is much lower there, amounting to 10.95% (against 23.43% in the basin of the Vistula).

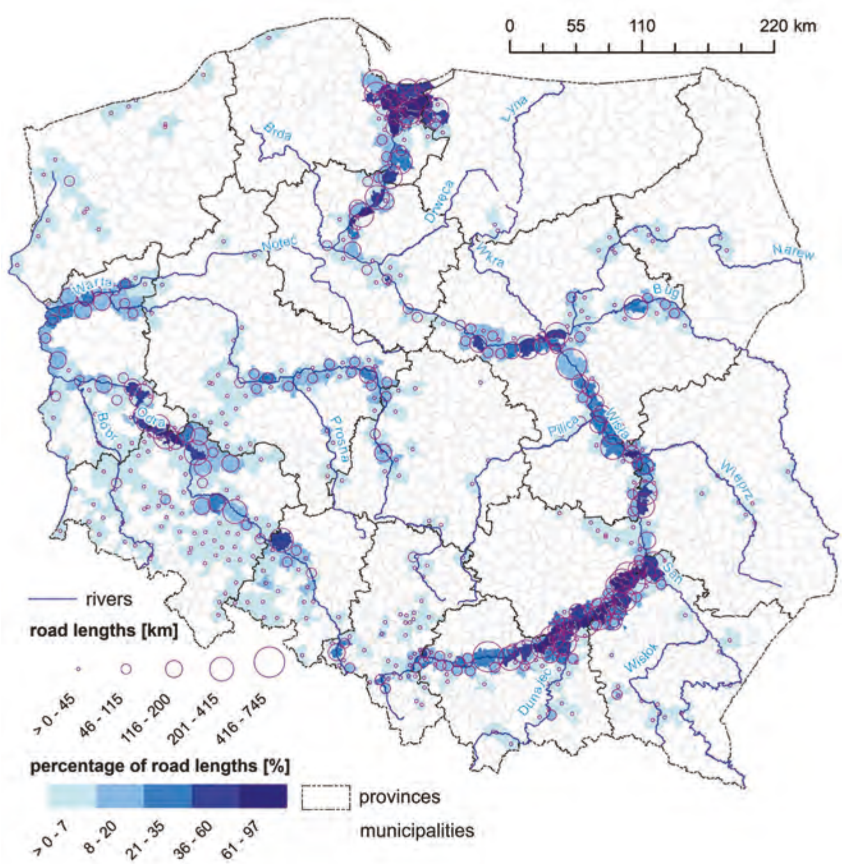


Figure 4.11. The length of flooded road sections and their percentage against the total length of roads in municipalities in the event of a flood due to a complete breach of a stopbank in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

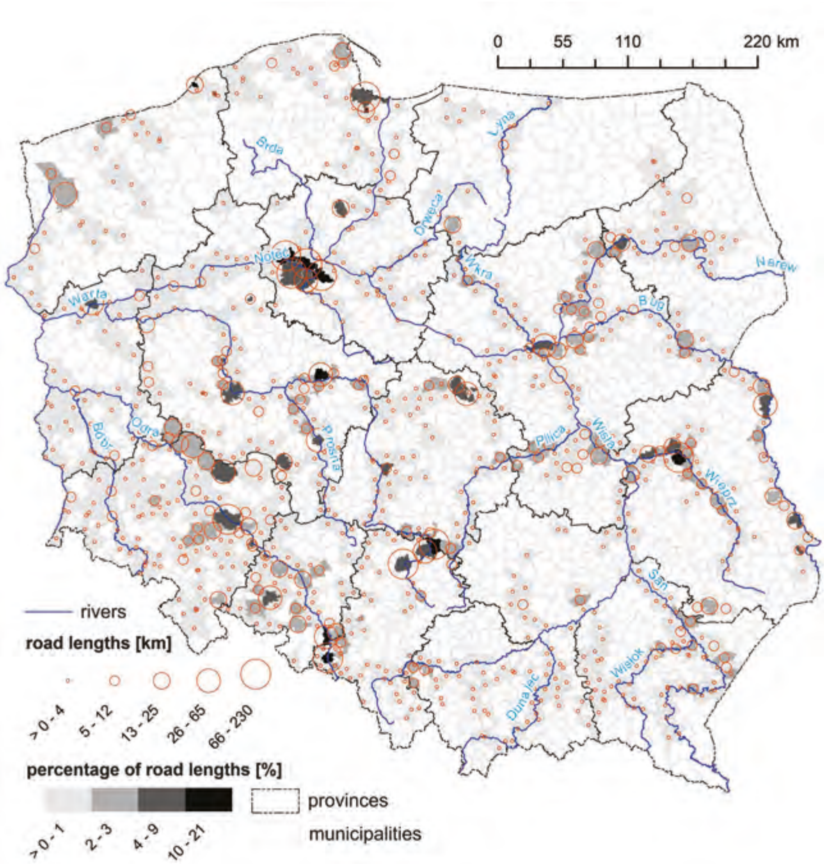


Figure 4.12. The length of "cut-off" road sections and their percentage against the total length of roads in municipalities in the event of a flood with a 10% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

In 855 municipalities, a flood with a high probability of occurrence would cause some uninundated sections of the road network to be "cut off". On average, the percentage of the cumulative length of such sections against the total length of the network per municipality equals 0.74%. Despite looking insignificant, this percentage is, however, quite variable (the standard deviation is 1.88 percentage points). The municipalities at highest risk of this phenomenon are Darłowo, Nakło upon Noteć, and Gidle, where the percentage in question exceeds 15%. Lublin Province is also particularly at risk (on a regional scale) as the average percentage of excluded road network sections per municipality is 4.50%

(63 municipalities). The largest group of municipalities where road infrastructure sections would be "cut off" are found in Masovian Province (101 municipalities), however, this problem is less severe there as it concerns an average of 2.90% of the entire network per municipality. Moreover, for all affected municipalities, a weak correlation between the cumulative length of inundated roads per municipality and the cumulative length of "cut-off" roads is observed (the Pearson correlation coefficient is 0.22) (Figure 4.12).

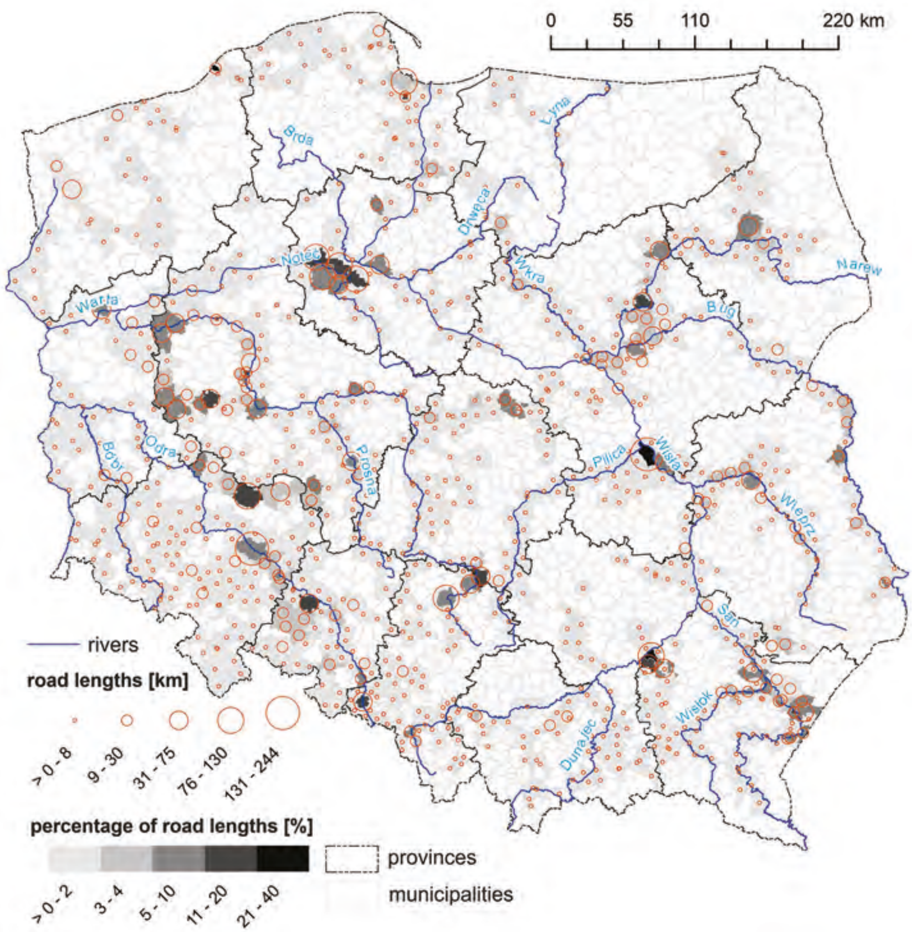


Figure 4.13. The length of "cut-off" road sections and their percentage against the total length of roads in municipalities in the event of a fluvial flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

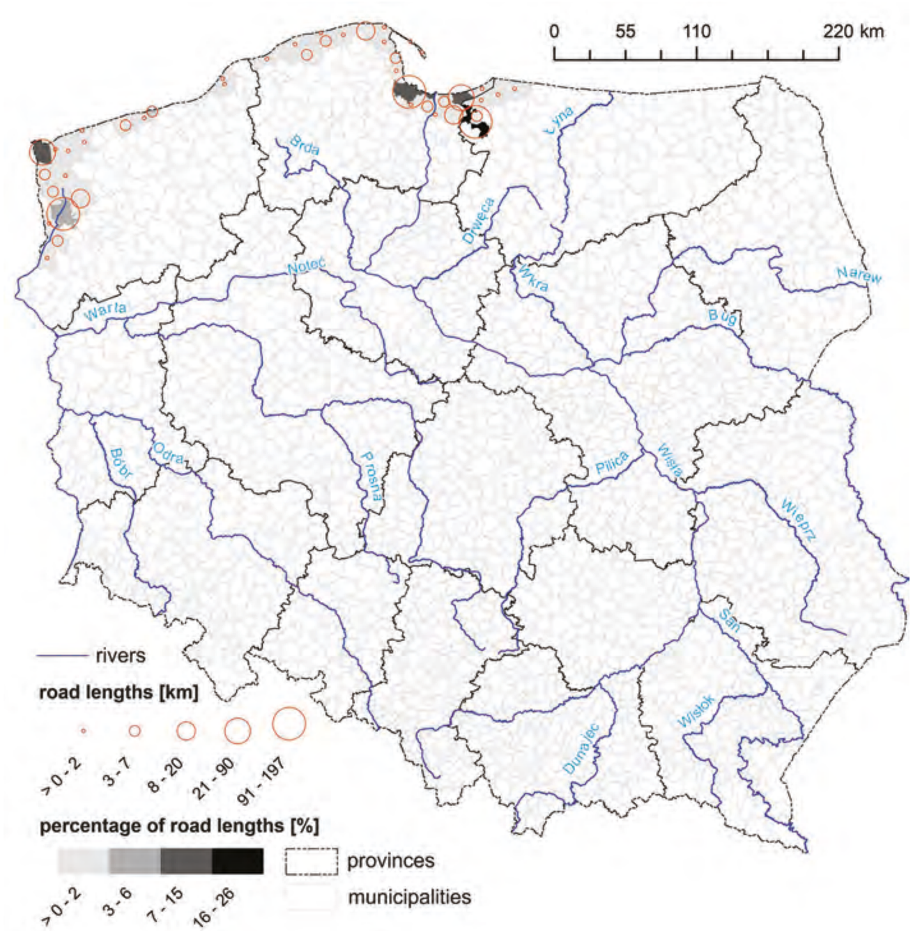


Figure 4.14. The length of "cut-off" road sections and their percentage against the total length of roads in municipalities in the event of a coastal flood with a 1% probability of occurrence in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

Compared to the scenario where there is a flood of high probability, a fluvial flood with a 1% probability of occurrence increases the number of municipalities where sections of the road network would be "cut off" by 65. The average percentage of their length also increases (to 1.05%) with a standard deviation of 2.78 percentage points. In this scenario, there are municipalities (Magnuszew, Borowa, Darłowo) where this percentage exceeds 20% of the total road network per municipality. However, the most vulnerable is Subcarpathian Province

(76 municipalities), even though its average (2.09%) is clearly lower than for the region most vulnerable to floods with a 10% probability of occurrence. As regards the largest number of municipalities affected, Lower Silesia ranks highest (107 municipalities; with an average of 0.82%). The dependence on how intense the flooding of the network is becomes more pronounced in this flood scenario (0.39), although it is still weak.

In the event of a coastal flood with a 1% probability of occurrence, parts of the road network in 44 municipalities would be "cut off" (Figure 4.14). In Elbląg, this would affect over 25% of the total length of the road infrastructure, while Sztutowo and Świnoujście would face a situation where over 12% of the total length of the road network would be rendered unusable – despite not being inundated. However, less than 1% of the municipal road networks (35) in this scenario would be affected by flooding. Equally imperceptible would be the correlation with the cumulative lengths of flooded sections of the road network.

The least severe effects as regards flood-related exclusions of road network sections arise from the scenario where there is a flood due to a complete breach of the protective structure of the service strip. Only 30 municipalities are affected, among which the highest exclusions (albeit only slightly exceeding 5% per municipality) would be observed in Cedry Wielkie, while the average for all municipalities is only 1.07% (Figure 4.15).

Finally, the last scenario, where there is a flood due to a complete breach of stopbanks, seems to be most relevant when the cumulative length of inundated road sections per municipality is analysed (the Pearson correlation coefficient is 0.46). In this scenario, the "cut-off" sections would be observed in 402 municipalities, affecting, on average, 1.35% of the total road network. However, this rises to over 2% in municipalities in Warmian-Masurian Province (it must be stressed, however, that this elevated average is calculated for only six municipalities). In Lower Silesian Province, as many as 56 municipalities would be affected, but here the average percentage amounts to only 1.13% (Figure 4.16). In absolute terms, the provinces of Masovia, Lesser Poland, and Lower Silesia would suffer the most when parts of the road network were "cut off" by floodwaters.

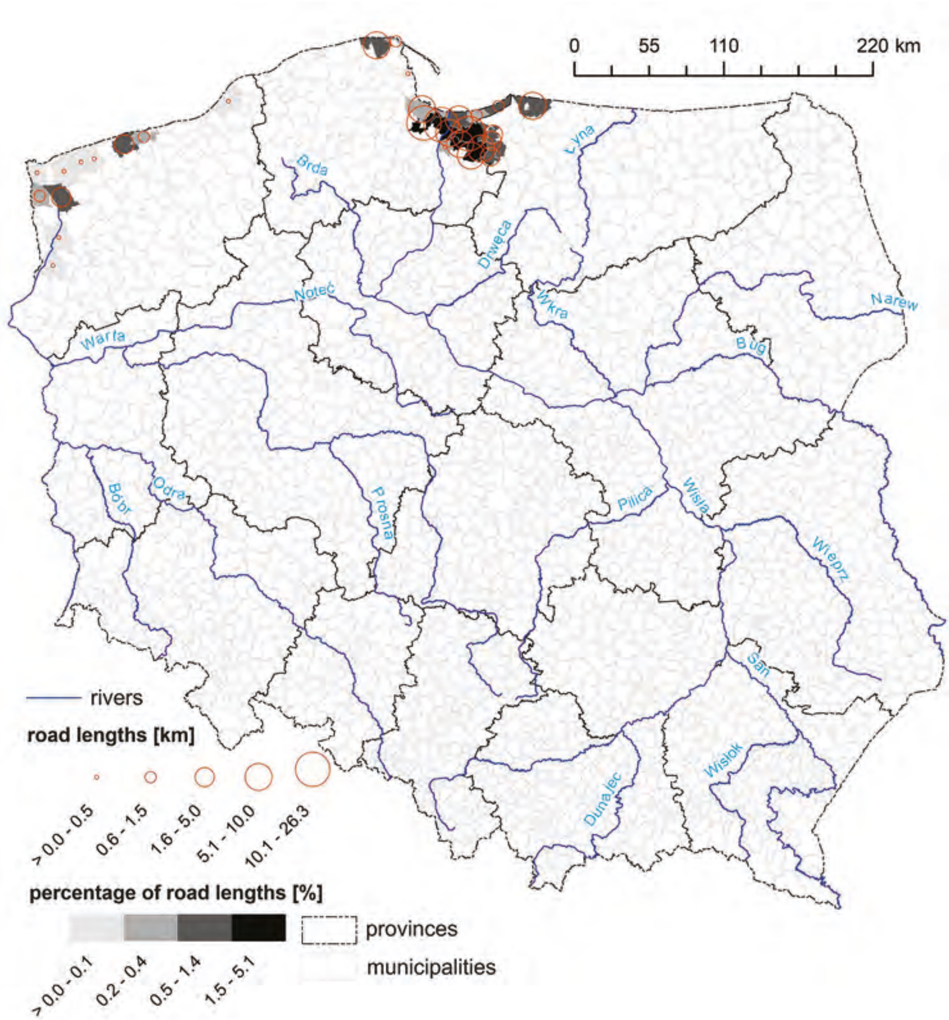


Figure 4.15. The length of "cut-off" road sections and their percentage against the total length of roads in municipalities in the event of a flood due to a complete breach of the protective structure of the service strip in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

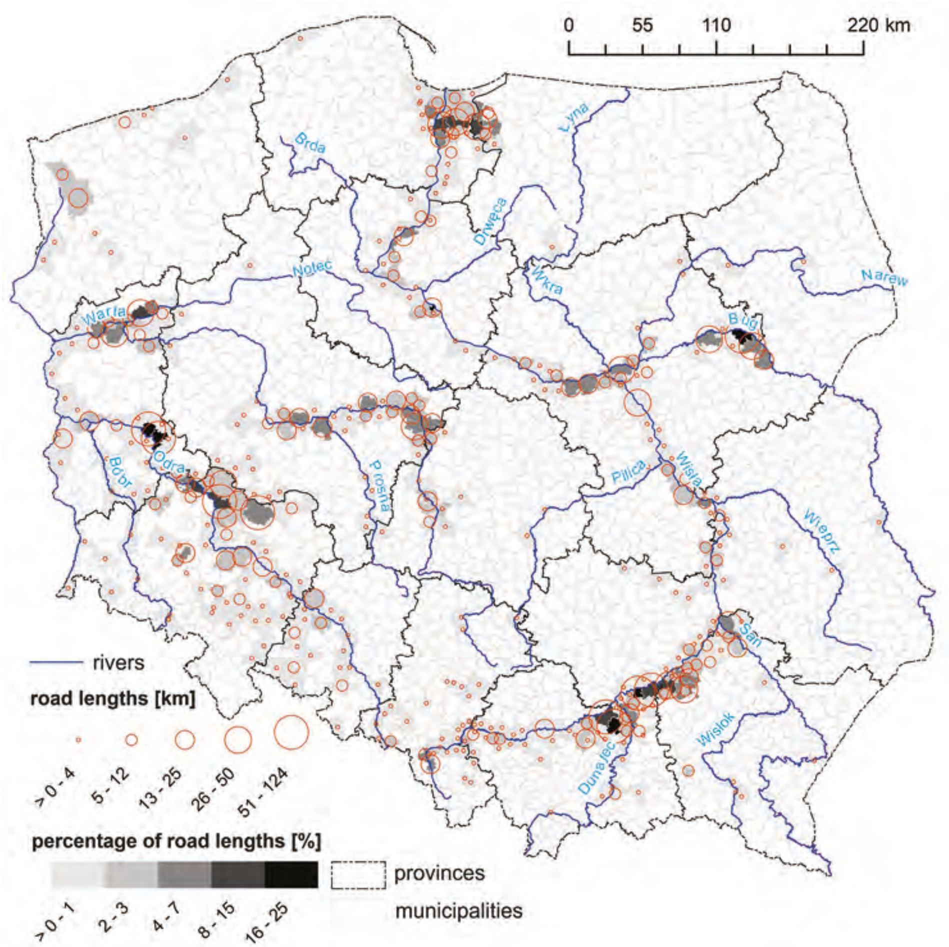


Figure 4.16. The length of "cut-off" road sections and their percentage against the total length of roads in municipalities in the event of a flood due to a complete breach of a stopbank in Poland in 2019

Source: own elaboration based on data from flood hazard maps and flood risk maps by the State Water Holding Polish Waters (2019) and the Database of Topographic Objects

5

FLOOD VULNERABILITY INDICES FOR PASSENGER ROAD TRANSPORT

Once the sections of the road network at risk of flooding or "cut off" from the rest of the network in the different flood scenarios were identified, it was necessary to analyse how their inaccessibility might affect the performance of the transport system. To this end, the scale and spatial differentiation of flood-related changes in transport accessibility and road network load were examined for each scenario, taking into account the probability of occurrence, the type of damage (source) that caused the flood, and its spatial scope. The analysis was preceded by a review of studies on traffic speed models and a description of the assumptions behind the model that underpinned the research on accessibility and road network load.

Importantly, the impact of a disaster (here: flooding) on road transport is not just limited to disruption to the road network and the accompanying adaptation of travel routes. What also changes is the behaviour of drivers (Hamilton et al. 2018, Aerts et al. 2018, Ruin et al. 2017, Drobot et al. 2007), who – depending on their personal traits and the disaster itself (its dynamics, etc.) – may consciously or subconsciously alter their driving behaviour, postpone the journey, change the destination, choose a different mode of transport or eschew travelling altogether. These issues, extremely important as they are, require a separate study to research them more thoroughly.

5.1. Traffic speed modelling

5.1.1. Introduction and review of studies

The very first isochrone maps (with daily isochrones) are believed to have been applied by Galton (1881). Subsequent studies by Schjerning (1903), Hassinger (1910), Eckert (1925), Rewieńska (1929), Wąsowicz (1934), etc. were based on the creation of analogue, hand-drawn isochrones on maps (Bielecka and Bober 2013, Śleszyński 2014). Only from the late 20th century have computer tools been employed in research. Whichever technique is used, a key aspect has always been the measurement of temporal distance, which is a derivative of the speed at which the selected mode of transport can travel. When common modes of transport (plane, rail, bus, etc.) are analysed, the researcher can use the fixed timetables that show both transit times and frequencies (Warakomska 1993). However, for studies of individual accessibility (e.g., trips by passenger car), analysts must adopt official speed limits or employ traffic speed models for the greatest accuracy possible. This stems from a number of factors. Firstly, personal means of transport are used in a more spontaneous manner and differ considerably from one another in maximum speed, acceleration, ability to negotiate hills, etc. Differences also emerge in the drivers' behaviour (individual psycho-physical traits) and the space where transport takes place following changes in traffic organisation (speed limits, etc.) and road infrastructure (different quality and capacity of the road network, depending on the land use and development in the vicinity of the roads, etc.).

Given the diversity of the factors that affect travel speed, various simplifications are necessary when one creates speed models. In addition, their complexity may also depend on the spatial size of the area they cover. The more spatially extensive the approach, the greater the simplicity of solutions and, thus, a drop in accuracy. Among the simplest approaches is the adoption of specific travel speeds for different road categories. At a time when congestion on roads was rare, this approach was common (Śleszyński 2014). In fact, some speed models are still based on official speed limits (Kowalski and Wiśniewski 2017) and the assumption that the degree of the level of free-flow traffic (LFFT) is unlimited. Due to the rise in car ownership and the escalating issue of congestion, these models are now considered inaccurate, and solutions today take into account those factors that lead to a reduction in official speed limits, i.e., road category and traffic density (Gaca et al. 2008). Some authors also choose to incorporate data on land use (Hunt et al. 2005), which allows them to obtain better estimates of the LFFT (traffic density, the presence of exits, etc.) (Borowska-Stefańska et al. 2020a).

A number of tools are employed to analyse traffic speed, including direct surveys that involve measurements of vehicle speeds at selected points (Dąbrowska-Loranc et al. 2015) or the researcher driving a specific road themselves and measuring travel speeds along it in line with predefined principles (Bartosiewicz and Pielesiak 2012). The former is usually applied to assess the level of road safety; however, the choice of measurement points and insufficient representativeness for analysing road networks renders this approach inapplicable in accessibility studies. The latter method allows the temporal accessibility of places to be examined, but only for the road along which the research was conducted, which means that there is no data for those sections of the road network where the research was not performed.

Another research approach to measure vehicle speeds involves analyses based on the vast pools of data capturing the position of vehicles within the transport network. It includes data acquired by road traffic management bodies, which is mainly used in intelligent transport systems and collected as part of area-based traffic organisation systems or for information purposes, (e.g., to be displayed on variable information signs and boards, etc.). This information, which is based on measurements of identified vehicles (usually using ANPR technology), allows the researcher to determine vehicle travel times upon appropriate data aggregation (Kim et al. 2005, Borowska-Stefańska et al. 2019c). This information and the analyses based on this data, however, also fail to provide travel times for sections of the network that have not been monitored.

Another method to obtain empirical data on vehicle speeds within a transport network is through analyses of information from metered vehicles, usually taxis (Liu et al. 2009, Deng et al. 2015). This allows for analyses of travel speeds across a wider network, but the results are hardly representative since they are limited to a rather small group of professional drivers. Further methods of collecting vehicle speed data involve monitoring not the vehicles and the transport network, but individual users. Here, big data collected by mobile phone network operators is employed (Caceres et al. 2008, Gadziński 2018). However, Rose (2006) points out that even though mobile phones seem to offer attractive prospects as sensors for traffic measurement, there are still issues to be solved, related to data accuracy and reliability (incidental failures of technology that compromise the quality of raw data), sample size and representativeness, as well as, obviously, security and privacy. Another source of big data are global corporations that provide navigation tools and location tracking solutions. This data comes from GPS trackers in satnav devices and smartphones used by drivers, enabling the capture of travel times on an unprecedented scale. Although this data is sometimes employed in accessibility studies (Wiśniewski 2016, Cui, Levinson 2018, Borowska-Stefańska et al. 2019c), it has its limitations, mainly related to the lack of comprehensive information on the algorithm that determines travel times.

Although the said approaches (based on empirical measurements) are extremely valuable for analytical purposes, each is burdened with a significant level of ambiguity, if only due to the insufficient representativeness of the driver's psycho-physical profile and road categories, and the fact that the data easily becomes obsolete upon any changes in the transport infrastructure. Therefore, to map the largest possible number of inter-relationships on a highly detailed network theoretical traffic speed models are required. However, it must be stressed that even these are sometimes calibrated based on empirical research methods, including those presented above.

Essentially, the simplest vehicle traffic speed model is not based on theory, but official speed limits. In this model, designated speed limits for different road categories are assigned to individual sections of the road network. This type of model was commonly employed in the past, when congestion was not a major issue (Rowicki, 1934), but it still may be applied today due to its simplicity

(Wiśniewski 2015, Rosik et al. 2020). Besides strictly geographical studies (based on actual topologies of the road network), one example is Chalfen and Kamińska (2013), who built a hypothetical urban transport network to determine how to employ an algorithm for the shortest travel path from a single trip origin in a graph. They arbitrarily set the accepted speed to 10 km/h in the city centre, 30 km/h in the zone between the city centre and the peripheries, and 50 km/h in the peripheries. Nowadays, the main problem with such models is that they do not take into account the level of free-flow traffic (LFFT), which is a major factor affecting speeds (especially on congested roads). Together with technological progress (modern means of transport, road engineering, etc.), the LFFT for car speeds adopted in studies on accessibility undergoes changes over time – changes that are also affected by road category. In speed modelling in Switzerland (between 1950 and 2000), changes in average speeds pertain to an increase in traffic speeds on most roads outside built-up areas (Fröhlich and Axhausen 2002). Attempts to incorporate traffic density into Polish studies on transport geography have also been made for the metropolitan areas of Warsaw, Kraków and Łódź, among others. For the Kraków area, a gradual speed reduction was adopted (by 5 km/h) that depended on traffic density, road curvature and road quality, while delays resulting from travelling across grade-separated junctions (different for each junction type) and city centres (corresponding to city sizes) were also added to the travel time calculated. The speeds determined on each type of section were adopted as the input speed, i.e., for the highest LFFT (Guzik 2011).

For the Łódź region, accessibility studies have been based on different types of speed models. Bartosiewicz and Pielesiak (2012) selected seven roads and created a model of the theoretical travel time on these roads, based on the maximum permissible speed and adding 30 seconds to the thus calculated travel time for each set of traffic lights. The model was uncalibrated and aimed at assessing the performance and capacity of the said roads by using empirical measurements taken by the authors (delay analysis against a theoretical benchmark). Other solutions for Łódź-based research include speed models that rely on macrosimulation traffic modelling (Borowska-Stefańska et al. 2019a, Wiśniewski et al. 2020a). The authors presented methods for studying transport accessibility in the event of a natural disaster based on the results of traffic macrosimulations and using models for regional and national scales. In this type of traffic speed model, the travel time between origins and destinations is the resultant of the anticipated (modelled) distribution of traffic over the network (against its capacity) and the presumed speed that could be reached for the LFFT.

A speed model developed for the Warsaw area incorporates a number of factors affecting travel times, with the primary variable being the official speed limit reduced by the following factors – the number of residents within an area of 5 kilometres of the road section, the percentage of the built-up areas within

100 metres of the road section, and the relief – which could, in theory, lead to drops in observed speeds. These affect the speed reduction within the model differently, as various functions were adopted for different road types. As regards the country's external borders, additional time was applied for border checks depending on the scenario (Komornicki et al. 2011, Rosik 2012).

Among the methodological approaches to modelling traffic speeds outside Poland, Bateman et al. (1996, 1999) employed official data from the Department for Transport in their speed model. The data was verified and compared against speeds from other studies and sources (including data from route-planning applications). Any further calibration of the model was based on the researchers' own personal experience. In general, the complexity of the model and the sources used to build and calibrate it depend largely on the scope of the research itself (Table 5.1).

Table 5.1. Factors affecting passenger car speeds in selected speed models

Research application	Area of application	Factors considered
Rosik et al. 2020	continent – Europe	administrative (set speed limit for the highest road category)
Gutiérrez and Urbano 1996		set speed limits for each road class
Kyte et al. 2000	country – the USA	Highway Capacity Manual, wind velocity, rainfall intensity and road conditions
Fröhlich and Axhausen 2004	country – Switzerland	average speeds adopted for each road type taken from other studies
Bateman et al. 1996	country – Great Britain	data from the official sources of the Department of Transport verified using, inter alia, route-planning applications and calibrated on the basis of subjective (personal) experience
Komornicki et al. 2009	country – Poland	administrative (official speed limits); technical (road category); demand-related (population distribution): natural (topography)
Stępniak and Rosik 2013		
Rosik 2012		
Kowalski and Wiśniewski 2019		official speed limits
Borowska-Stefańska et al. 2019a		a speed model based on simulations of network load following a four-step traffic model
Wiśniewski et al. 2020a	region – Greater Poland (Poland)	
Borowska-Stefańska and Wiśniewski 2018	region – Masovia (Poland)	official speed limits
Lovett et al. 2002	region – Cambridgeshire, Norfolk and Suffolk (United Kingdom)	data from the official sources of the Department for Transport calibrated for local conditions
Li et al. 2011	city – Wuhan (China)	floating car data/measurements
Salonen and Toivonen 2013	city– Helsinki (Finland)	
Borowska-Stefańska et al. 2019c	city – Łódź (Poland)	results of ITS measurements (ANPR cordons)

Source: own elaboration.

Traffic speed modelling is a complex issue due to the high entropy of transport systems and their surroundings (Przybyszewski and Wędrowska 2005). Although road traffic management bodies may specify permissible speeds, in congested systems and periods these are more likely to become the upper limit of the speed rather than the operational capacity of individual sections. Ongoing changes in the socio-economic environment; technical progress which results in the upgrading of existing modes of transport and the emergence of new ones; and advances in engineering and construction (fields that greatly impact transport networks) are all factors that add further variables to the actual speeds on the network (Dziadek 1991, Borowska-Stefańska et al. 2020a).

Changes which stem from technological and societal progress or climate change have long-lasting effects. They are also the product of homeostasis in adapting the shape of transport systems and settlement units in line with organicist theories and the result of fluctuations in economic prosperity. This constant change means traffic modelling often requires regular calibrations so that the model can be appropriately adapted to the specific spatial conditions and individual regional or even local characteristics. These are a derivative of inter-subsystems relationships within the transport system and inter-system relationships between the transport system and its surroundings. Owing to the multitude of possible interactions between different subsystems within the transport system, further studies to accurately assess speeds on the transport network should be conducted and compared to actual situations (Helbing et al. 2002, Jeihani and Ardeshiri 2017).

Even under "normal" operating conditions, all the factors mentioned make capturing accurate traffic speeds difficult. This challenge becomes even more formidable, however, when one strives to determine speeds under non-typical conditions, when the equilibrium of the transport system has been disturbed. Then, it is necessary to determine the vulnerability of the network and the probability of events that may upset the equilibrium. Alas, it is often problematic to unambiguously and precisely identify those specific places where disturbances may occur which change the spatial distribution of traffic. Major challenges are also faced by researchers who model traffic during a natural disaster, when entropy rises dramatically, thereby rendering models virtually non-calibratable. To make matters worse, some disasters occur so infrequently that the experience of previous events is often of no analytical value (e.g., due to the changes in the transport network, land use, and the transport behaviour of residents that have all occurred between the two events) (Bland et al. 1997, Sadri et al. 2014). Therefore, researchers often have no choice but to adopt travel matrices and baseline traffic distribution in the network from traffic models calibrated under "normal" conditions (Borowska-Stefańska et al. 2019a).

The level of free-flow traffic (LFFT) is the fundamental parameter that determines the achievable operating speeds (besides official speed limits). It is a product of the infrastructure capacity and the traffic density observed there. Parameters that can impact capacity include: turning radii, the width and number of lanes, carriageway separation or its absence, the method of toll collection, the organisation of traffic at junctions, and the number of junctions and exits. Traffic density, on the other hand, is determined by: the mobility level of the population, the modal split, and the shape of the transport network and its location (Transportation Research Board of the National Academies 2010, Leyn and Vortisch 2015).

In the literature on modelling natural factors that affect traffic speeds, a distinction is made between those that impact the network periodically and those that do so permanently. The former include precipitation, e.g., rain, which causes a reduction in traffic speeds proportional to its intensity; and snow, which reduces speeds more severely than rain (Tsapakis et al. 2013); fog (the more intense, the lower the speeds) (Hranac et al. 2006, Maze et al. 2006), and strong wind, which reduces speeds to a lesser degree than the factors listed above (Sabir et al. 2011). Natural factors that affect speeds permanently include relief – which may impact both the longitudinal profile of the road; the number of curves in locations with significant inclines and declines (Rosik and Śleszyński 2009); and the hydrographic network, which necessitates the erection of bridges that often become bottlenecks for the transport system (Borowska-Stefańska et al. 2020a). Cools et al. (2010) and Keay and Simmonds (2005) state that natural factors also shape road network load, thereby indirectly impacting traffic speeds by affecting people's mobility and preferences for certain modes of transport.

5.1.2. Description of the model

Construction of a traffic speed model requires a vector model for the road network of the study area to be prepared. To ensure the highest possible realism of the results on flood-related changes in transport accessibility and road network load, it was necessary to prepare a road network that most accurately reflected the course of the actual roads. Its final form represents a compromise between the highest accuracy of the results and the computational and perceptual capabilities available. A road network that incorporates sections representing the lowest public road classes not only makes it possible to include the largest possible set of sections potentially inundated by floodwaters, but also to map the flexibility of the transport network while taking into account alternative travel routes. In studies that do not need to consider any road closures within the network, the importance of roads of the lowest category is marginal (unless they are the only route to a given settlement or transport region), since they are rarely part of the route that offers the shortest travel time, which is where the first principle of Wardrop applies (Wardrop 1952). However, in the study presented here, these roads can become important in some flood scenarios (e.g., being the only route to bypass a flooded section).

Data from the following sources was used to develop the network for this study: data from the Database of Topographic Objects provided by the Head Office of Land Surveying and Cartography; layers of images presenting the road network from OpenStreetMap; databases of the General Directorate for National Roads and Motorways; and data from regional road authorities. This broad spectrum of data was then thoroughly verified for accuracy, completeness and up-to-datedness, and used to build a network that represented the whole territory of Poland, including a strip of several dozen kilometres around its borders (another variable that rendered the results more realistic). Each road section was given an attribute allocating it to a road category: national road (NR), regional road (RR), district road (DR), municipal road (MR), other (OR); and a road class: motorway (MW), expressway (EW), fast traffic trunk road (FTTR), main road (MR), collector road (CR), local road (LR) and access road (AR).

How different road classes are distinguished and prioritised mainly depends on the transport organisation adopted by a given country. The Vienna Convention on Road Signs and Signals may be a major guideline on the regulations on road traffic for local legislators, and yet it is of indirect relevance for the technical parameters of road types. In some countries, the technical parameters of a given road class depend on where the road is located within the settlement network ("extra-urban" and "urban" roads). In Poland, however, the names of road classes are the same for roads running through cities and non-built-up areas (even if their parameters differ). Road classes are distinguished and prioritised based on their technical parameters, the highest being motorways and expressways. These are roads of limited accessibility (access forbidden for particular modes of transport), designed and built for high-speed vehicle traffic. In general, the official speed limit for passenger cars (excluding site-specific restrictions) is 140 km/h for motorways, and 120 and 100 km/h for dual and single carriageway expressways. An additional official speed limit (80 km/h) applies to vehicles exceeding 3.5 tonnes (gross vehicle mass). Ranked next are fast traffic trunk roads and main roads, which (along with motorways and expressways) are part of the road system meant to provide efficient connections between major transport regions. When compared to motorways and expressways, these roads offer lower transport efficiency due to the inferior technical parameters that partly impede smooth passage. The remaining types of roads primarily serve to channel traffic on smaller, supra-local and local scales. These include collector roads (class: CR), local roads (class: LR) and access roads (class: AR). Occasionally, the aforementioned hierarchy of roads is expanded with internal roads (although they are not a separate road class). A division into road categories (by function performed) is also applied but – from an infrastructural perspective – the importance of this division in shaping mobility is secondary to the role of road classes.

A prerequisite in building the speed model and then determining the distribution of traffic over the network for the chosen trip motivations was knowing the number of lanes. Additionally, all segments were assigned to one of the three classes determining the built-up density in the vicinity (non-built-up areas, built-up areas, and partially built-up areas), following an approach proposed by Szczuraszek and Chmielewski (2017). This variable was taken into account upon the analysis of data on the total surface area of buildings near the road (the Database of Topographic Objects), which was used to construct the traffic speed model within a strip of 100 metres around a given road section. The obtained values for individual categories and classes of sections within the road network were arranged following the Jenks Natural Breaks Classification Method, where three classes were distinguished to represent the intensity of built-up development in the vicinity of road sections. This rendered it possible to determine sections that ran through areas of relatively high built-up density (the previously named: "built-up areas"), of relatively low built-up density (the previously named: "non-built-up areas"), and mixed areas (the previously named: "partially built-up areas"). In this case, built-up areas are understood as road sections running through any built-up areas, regardless of how the road is separated from its surroundings, which differs slightly from the interpretation in the Polish law, where – for instance – motorways are not deemed as running through (i.e., being part of) built-up areas.

Ultimately, the traffic speed model took into consideration nine types of road sections: motorways (MW), expressways (EW), national roads (FTTR), regional roads (FTTR, MR), district roads (FTTR, MR, CR), municipal roads type I (FTTR, MR, CR), municipal roads type II (LR), municipal roads type III (AR), and other (AR), all of which were conditioned by the built-up density in their vicinity. It was assumed that the most fundamental factors limiting speeds are the official speed limits and the technical parameters of the road/road conditions (expressed as speeds in free-flow traffic applied in simulation modelling of traffic). These restrictions constituted a base for further calculations, on the assumption that a drop in the level of free-flow traffic (LFFT) should translate into a decrease in travel speeds. The computational procedure entailed a number of stages including source data collection and processing, as well as model calibration (Figure 5.1).

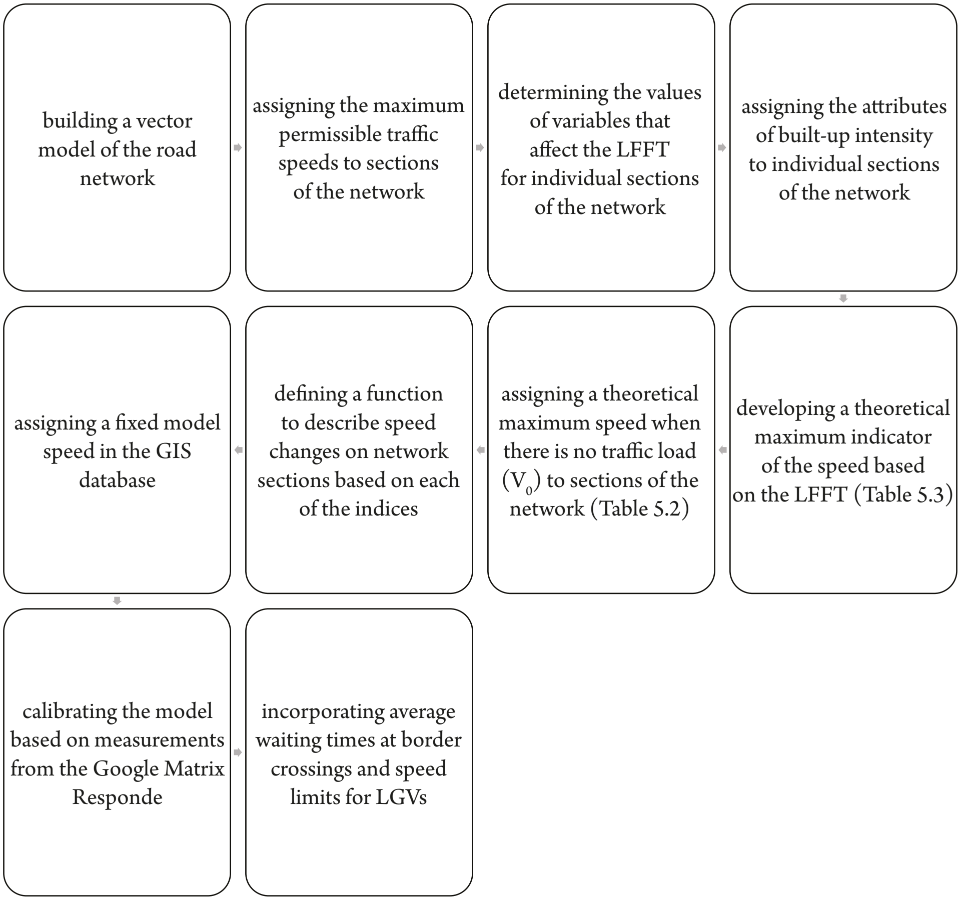


Figure 5.1. The research procedure for building a traffic speed model
Source: own elaboration

Each section of the road network was given a maximum speed under applicable laws, compliant with regulations imposed by local road authorities. The speed V_0 was assigned for each section following the guidelines by Szczuraszek and Chmielewski (2017) (Table 5.2).

Table 5.2. Capacity and speed in free-flow traffic by road section type.

Type	Road	No. of lanes	Capacity [veh/h]	Speed in free-flow traffic [km/h]
1	motorway 2x2	2	1,955	125
2	expressway 2x2	2	1,860	111
3	expressway 2x1	1	1,491	90
4	national 2x2 L	2	1,775	97
5	national 2x2 M	2	1,535	84
6	national 2x2 H	2	1,292	60
7	national 1x2 L	1	1,431	86
8	national 1x2 M	1	1,258	76
9	national 1x2 H	1	1,086	65
10	regional 2x2 L*	2	1,370	83
11	regional 2x2 M*	2	1,230	74
12	regional 2x2 H	2	1,292	60
13	regional 1x2 L	1	1,230	74
14	regional 1x2 M	1	1,142	69
15	regional 1x2 H	1	1,047	63
16	district 1x2 L	1	1,182	71
17	district 1x2 M	1	1,119	67
18	district 1x2 H	1	1,057	64
19	municipal 1x2 L	1	1,057	64
20	municipal 1x2 M	1	999	60
21	municipal 1x2 H	1	986	59
22	other	1	509	26

L – network section running through an area of low built-up density, H – network section running through an area of high built-up density, M – network section running through a "mixed" area.

* As there were no designated section types in Szczuraszek and Chmielewski (2017), the values for capacity and speed under free-flow traffic conditions were introduced as assigned for a seven-metre-wide regional road in a non-built-up area and a seven-metre-wide regional road in a partially built-up area.

Source: own compilation based on Szczuraszek and Chmielewski 2017.

Given the increase in road load and growing capacity restrictions, adjustments were made to vehicle travel speeds within the network based on the theoretical model of the level of free-flow traffic (LFFT). The key parameters determining the LFFT in the model were: the number of residents within 5 kilometres of the road, the density of the built-up areas within 100 metres of the road, and the degree of free-flow traffic expressed by the average road length between junctions (Table 5.3). For each of the 27 types of road sections, specified parameters were determined, bearing in mind that lower-category sections are usually roads without priority (yielding right of way) and offer greater legal and technical liberty concerning the location of new exits. However, the differences in speed begin to decrease when built-up density increases. The smaller speed reduction on some types of roads within built-up areas rather than outside them stems from a substantial change in input speed, which – outside built-up areas (maximum permissible speed = 90 km/h) – is often overstated when compared to actual (real-life) speeds on these roads.

Table 5.3. The maximum impact on speed reduction [where 1 = 100%, i.e., complete stoppage of traffic] of the three attributes that describe the LFFT in the model for particular types of road sections

Road section type		Junction density	Built-up density	No. of residents	Total
motorway	L	0	0.05	0.09	0.14
	M	0	0.06	0.1	0.16
	H	0	0.1	0.14	0.24
expressway	L	0	0.05	0.091	0.141
	M	0	0.06	0.105	0.165
	H	0	0.1	0.15	0.25
national road	L	0.01	0.15	0.175	0.335
	M	0.15	0.1	0.1	0.35
	H	0.32	0.01	0.05	0.38
regional road	L	0.0825	0.154114	0.204167	0.440781
	M	0.2375	0.102743	0.12	0.456909
	H	0.3775	0.010274	0.06	0.448191
district road	L	0.155	0.162014	0.221181	0.538194
	M	0.325	0.108009	0.13	0.559398
	H	0.435	0.010801	0.0813	0.527051
municipal road type I	L	0.2275	0.176597	0.230396	0.634493
	M	0.4125	0.117731	0.13	0.661886
	H	0.4925	0.011773	0.1229	0.62719
municipal road type II	L	0.251667	0.201597	0.235196	0.68846
	M	0.441667	0.134398	0.13	0.710462
	H	0.511667	0.01344	0.2063	0.731356
municipal road type III	L	0.275833	0.226597	0.239996	0.742426
	M	0.470833	0.151065	0.14	0.759039
	H	0.530833	0.015106	0.2167	0.762606
other	L	0.3	0.251597	0.244796	0.796393
	M	0.5	0.167731	0.14	0.807615
	H	0.55	0.016773	0.2271	0.793856

L – network section running through an area of low built-up density, H – network section running through an area of high built-up density, M – network section running through a "mixed" area.

Source: own elaboration based on Wiśniewski et al. (2020b).

During the next stage, the analyses of the number of residents, built-up density, and the number of junctions on individual road segments were conducted. The number of residents within 5 kilometres of the road section was determined and then compared to its length (thus, the length of the road section per resident was calculated). In this case, the study employed data on the number of people aggregated by street of residence (represented as a focal point), or – if this level of data aggregation was unavailable – by town, city or village of residence (also represented as a focal point). The built-up surface area within a 100-metre equidistance of the road was determined on the basis of data from the Database of Topographic Objects, by calculating how many meters of the road accrues per one square metre of built-up space. As regards the number of junctions, all existing ones were taken into consideration (including those with roads not included in the final version of the network model), and their number was compared to the length of a given section.

Next, the speed reduction function for the number of junctions on a given section (SR_J) was determined. Firstly, the average distance between junctions was calculated for each section under study (the quotient of the section length per number of junctions). At this stage, extreme observations were excluded from further calculations, on the assumption that 1% of the lowest values represent an extremely low LFFT (maximum value of traffic deceleration on a given type of section resulting from this factor) and 1% of the highest values represent a very high LFFT (there is no speed reduction on a given section due to this factor). For the remaining 98% of the observations, a maximum value of 1 was found against which the data was standardised. Then, the standardised data was processed using the following formula:

$$SR_J = \frac{\left(\frac{1}{1 + e^{-1(\beta x)}}\right)}{0{,}5} - 1$$

where:

$$\beta = \frac{1}{N}$$

The results were standardised based on the highest value. Due to the low value of parameter β, the function graph for this indicator, while essentially sigmoidal, resembles an exponential curve when plotted on a graph (Figure 5.2). The next step was to repeat the above procedure, but with the input data being the quotient of the section length and the surface area of built-up area (SR_B). The elimination of the extreme values involved discarding 40% of the extremely low (assuming that they contribute maximally to traffic deceleration) and 40% of the extremely high observations (assuming that their incidental occurrence contributes to no traffic deceleration). For the remaining 20% of road sections, a procedure was conducted identical to that for the speed reduction function caused by junction density (Figure 5.3).

The calculation of the speed reduction caused by the population who live in the vicinity of the road (SR_p) was based on the same procedure, but only the observations up to the 38th percentile were included, on the assumption that higher values are so small (1 resident per 980 linear metres of the road) that they have little impact on traffic speed. As a result, 38% of the network sections experience a defined speed reduction based on the previously presented function (Figure 5.4).

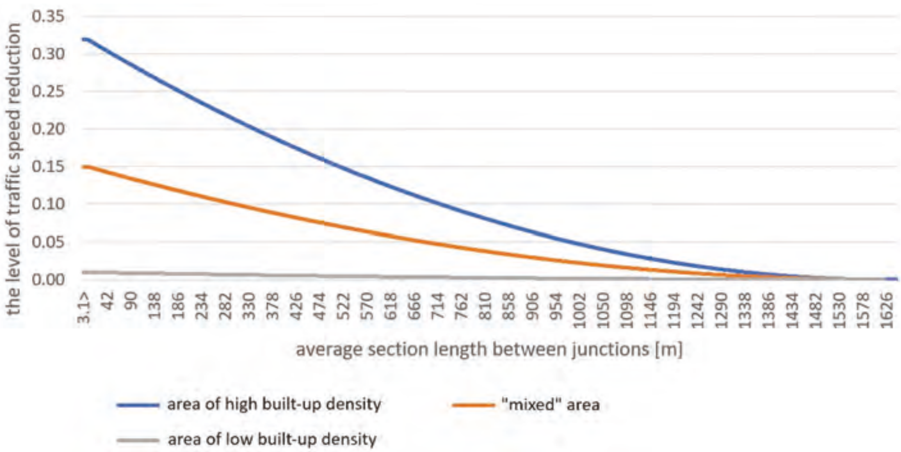


Figure 5.2. Speed reduction due to increased junction density for national roads
Source: own elaboration

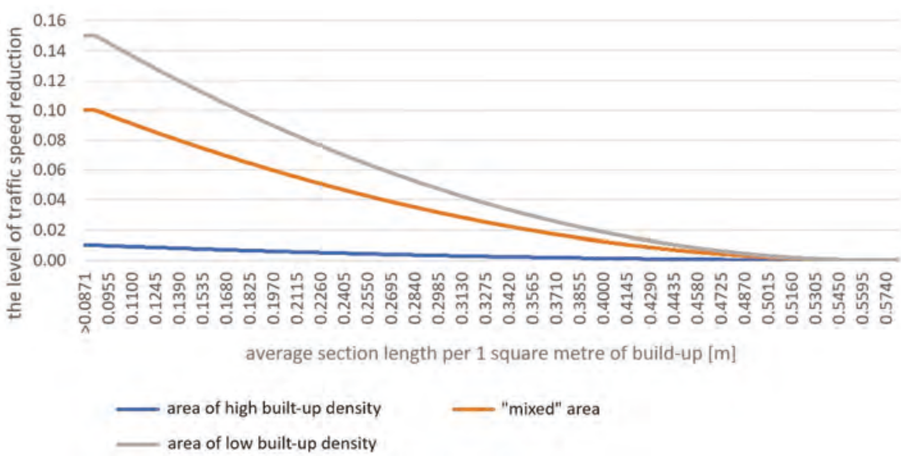


Figure 5.3. Speed reduction due to built-up density for national roads
Source: own elaboration

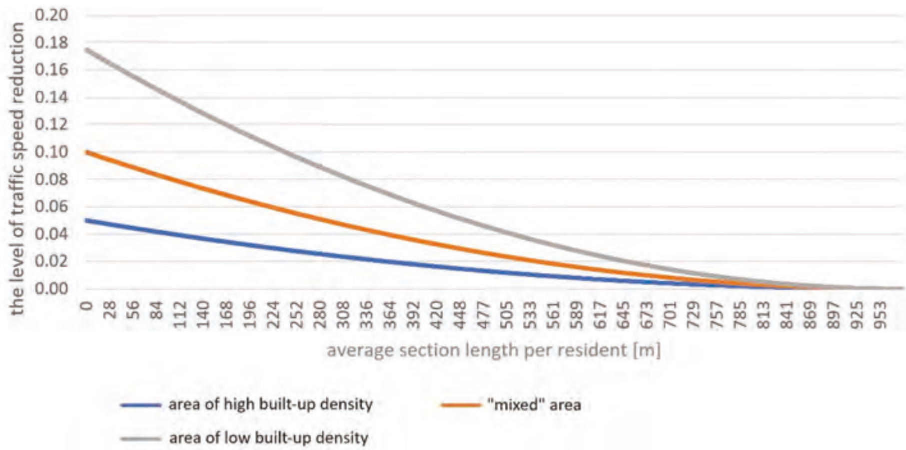


Figure 5.4. Speed reduction due to population density for national roads
Source: own elaboration

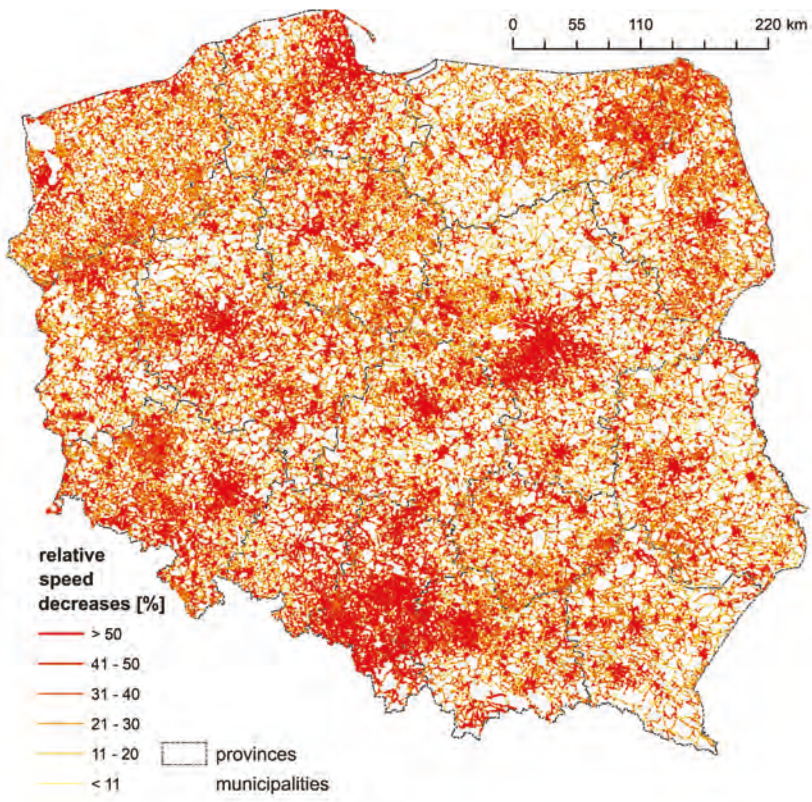


Figure 5.5. Relative decreases in travel speeds on the network section due to the application of the traffic speed model against official speed limits in Poland in 2019
Source: own elaboration

Next, the SR_J, SR_B and SR_P values were multiplied by the values that corresponded to them by virtue of their road section type and which determined the maximum impact on speed reduction (Table 5.3). The results were aggregated and used as the subtrahends for two calculations, where in the first the minuend was the code speed (Figure 5.5) and in the second the free-flow traffic speed (V_0). The average value from these two differences represents the speed applied in the speed model for passenger cars in Poland, which was later transferred (in the database format) to the GIS environment for further analysis.

Since there was no access to data on the number and distribution of the population for the areas outside Poland, it was assumed that this was a derivative of land use, and the function was based on data on the surface area of land use assigned to a given road section, except that the result was multiplied by the values of the indicator for the effect of population distribution in the vicinity of the road on the traffic speed reduction.

Figure 5.6. Travel speeds for network sections determined using the traffic speed model for Poland in 2019

Source: own elaboration

The next stage was calibration of the model, i.e., a series of simulations, the results of which returned the values and calculations presented above. The calibration was based on the popular database Google Matrix Respondes (Wiśniewski 2016; Borowska-Stefańska et al. 2019c; Rothfeld et al. 2019), which is a matrix of trips between selected settlements for long (over 200 km), medium (100–200 km), short (20–100 km), and ultrashort distances (below 20 km). Compared to the initial version of the model, the values of the β parameter during calibration changed to reduce the "thresholdness" of the applied function, as were the ranges of the extreme observations unrepresented by the function, which made it possible to determine the final traffic speed values for each network section (Figure 5.6, Table 5.4).

Table 5.4. Travel speed statistics by section type determined using the traffic speed model for Poland in 2019

Section type	**Speed [km/h]**			
	minimum	**mean**	**maximum**	**standard deviation**
motorway	95.0	119.5	125.0	6.2
expressway	77.3	104.0	111.0	7.2
national road	36.0	69.5	96.8	14.0
regional road	32.6	59.4	82.7	14.1
district road	26.4	48.9	71.0	13.9
municipal road type I	21.8	43.4	63.9	14.2
municipal road type II	16.6	37.2	59.0	10.4
municipal road type III	15.8	36.3	57.4	9.6
other	14.2	20.9	26.0	9.3

Source: own elaboration.

The final step in the construction of the traffic model was to adapt it to the cross-border relationships and to the transport tasks performed by large goods vehicles (so that possible further analyses could include LGVs). To this end, the traffic at the external borders of the Schengen Area was analysed and border waiting times reported by the Polish Border Patrol were added to travel times for sections running across the area. In order to represent the speed of LGVs, speed limits were incorporated into the existing model (for passenger vehicles), i.e., 80 km/h for all motorways, expressways and all other two-lane roads where official speed limits exceed 70 km/h.

5.2. Transport accessibility

5.2.1. Isochronous and cumulative accessibility

When determining the exposure of different elements of the road network to flooding, the researcher may not only reveal their importance to the operation of the entire road transport system (Nicholson and Du 1994), but also identify the flexibility of the road network to non-typical events, when the flood exceeds the robustness of individual sections (Blockley et al. 2012, Wan et al. 2017). The reliability of the road transport system during an extreme event also lies in the ability of its individual elements to take over and perform tasks that under "normal" conditions are not assigned to them (Jenelius and Mattsson 2012, Tukamuhabwa et al. 2015).

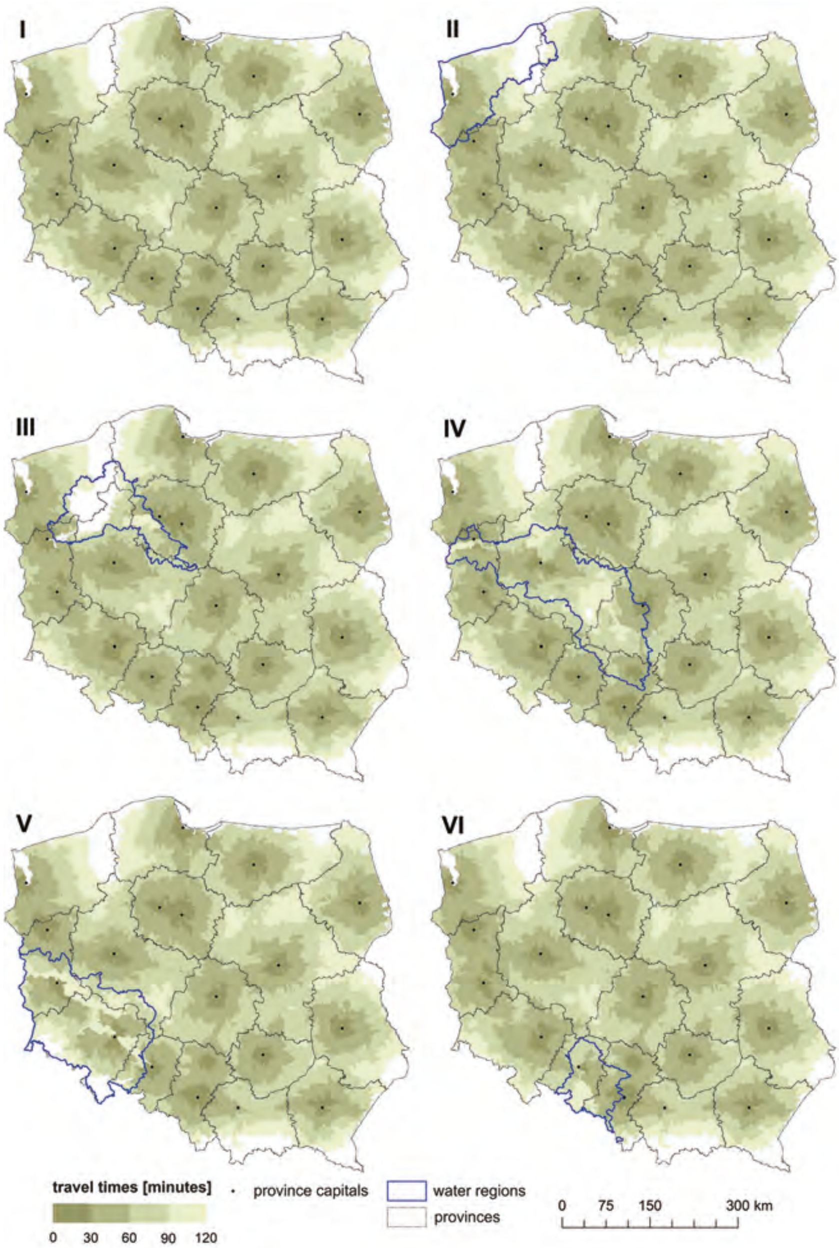
A number of methods to analyse transport accessibility are applied to capture how the properties of the road transport system affect its level of vulnerability to flooding, especially the vulnerability of its accessibility (Chen et al. 2007). Studies on the nature of transport accessibility itself (and the methodology to examine it) have been conducted for many years, resulting in a wealth of publications, both abroad (Vickerman et al. 1999, Gutierrez 2001, Spiekermann and Neubauer 2002, Geurs and Van Wee 2004, Geurs 2006, Neutens et al. 2010, Rietveld and Bruinsma 2012, Banister 2014, Guzman et al. 2017, Lucas et al. 2016, etc.), and in Poland (publications by the Institute of Geography and Spatial Organization at the Polish Academy of Sciences, including: Taylor 1998, 1999, Śleszyński 2009, Komornicki et al. 2010, Rosik 2012, 2014, Rosik et al. 2015, Rosik et al. 2017, etc., and by other research centres, including: Koźlak 2010, Sierpinski 2010, Wiskulski 2013, Guzik 2014, Gadzinski 2016, Zmuda-Trzebiatowski 2016, Kowalski and Wiśniewski 2017, etc.). The large number and complexity of the methods used to calculate (variously perceived) transport accessibility makes it difficult to give a single, most representative example of a paper that illustrates a given research trend. However, they all seem to accept a basic premise, i.e., accessibility is the ability for a correlation to emerge between at least two elements of a set (Komornicki et al. 2009) in a given socio-economic space. In other words, there must be at least two elements, being the origin and destination of accessibility, which are (unilaterally or bilaterally) accessible to each other, and a mode of transport which acts as a medium connecting these points in space and overcomes space decay represented by the various factors decreasing the attractiveness of trip destination(s). When accessibility is approached from this perspective, it can be perceived as a product of the transport system. However, when viewed through the economic lens, transport accessibility represents supply, where demand is the need to move (mobility). On the other hand, if one analyses this issue from the perspective of the market game related to Say's Law of Markets (Ładyka 2012), the higher the accessibility, the lower the costs of satisfying users' transport needs (whereby costs here are not the transport costs, but expense represented by travel time). Low costs may translate into increased demand, thereby reducing accessibility and increasing the cost of transport when the capacity of the road infrastructure to handle traffic is exhausted. This correlation is the premise behind a number of laws and paradoxes, including the Jevons Paradox and the Lewis-Mogridge Position (Burnewicz 2017).

In line with this market game, it is infrastructure (by providing efficient connections) that is among the major drivers of mobility. Besides roads (with their technical parameters, including the number and width of carriageways and lanes), infrastructure also includes car parks, service stations (including charging stations for EVs – a key factor in the era of growing electromobility), and intelligent transport systems. Importantly, improvements in transport accessibility do not only affect daily mobility, but also migration, of which Marchetti's constant is an explication (Marchetti 1994).

The said infrastructure-related factors are not the only element affecting transport demand. The spatio-functional structure and the resulting distribution of trip origins and destinations also play a role. The greater the distance between origins and destinations, the lower the propensity of transport system users to make such a trip. If they do undertake the journey, the distance significantly impacts the modal split of the means of transport they choose (Sierpiński 2012).

Since the presented study aims to determine how distance decay, modified by a non-typical factor (here: flooding), affects trips by passenger car between selected points in Poland (provincial capitals, focal points of municipalities, etc.), the obvious course of research is to apply methods for measuring transport accessibility. Among the wide spectrum of these (a comprehensive review of which was made by Rosik 2012), the approach of choice were methods not only to measure isochronous and cumulative accessibility (Bielecka and Filipczak 2010, Gadziński and Beim 2010, Olszewski et al. 2013, Śleszyński 2014, Śleszyński et al. 2015, Bul 2016), but also potential accessibility for short and long trips (Rosik 2012, Rosik et al. 2013, Rosik et al. 2015, Rosik and Stępniak 2015, Stępniak and Rosik 2018). Not only do they allow a vast set of source data to be incorporated into the study, but they also produce results that can be presented in a clear and easy-to-comprehend manner.

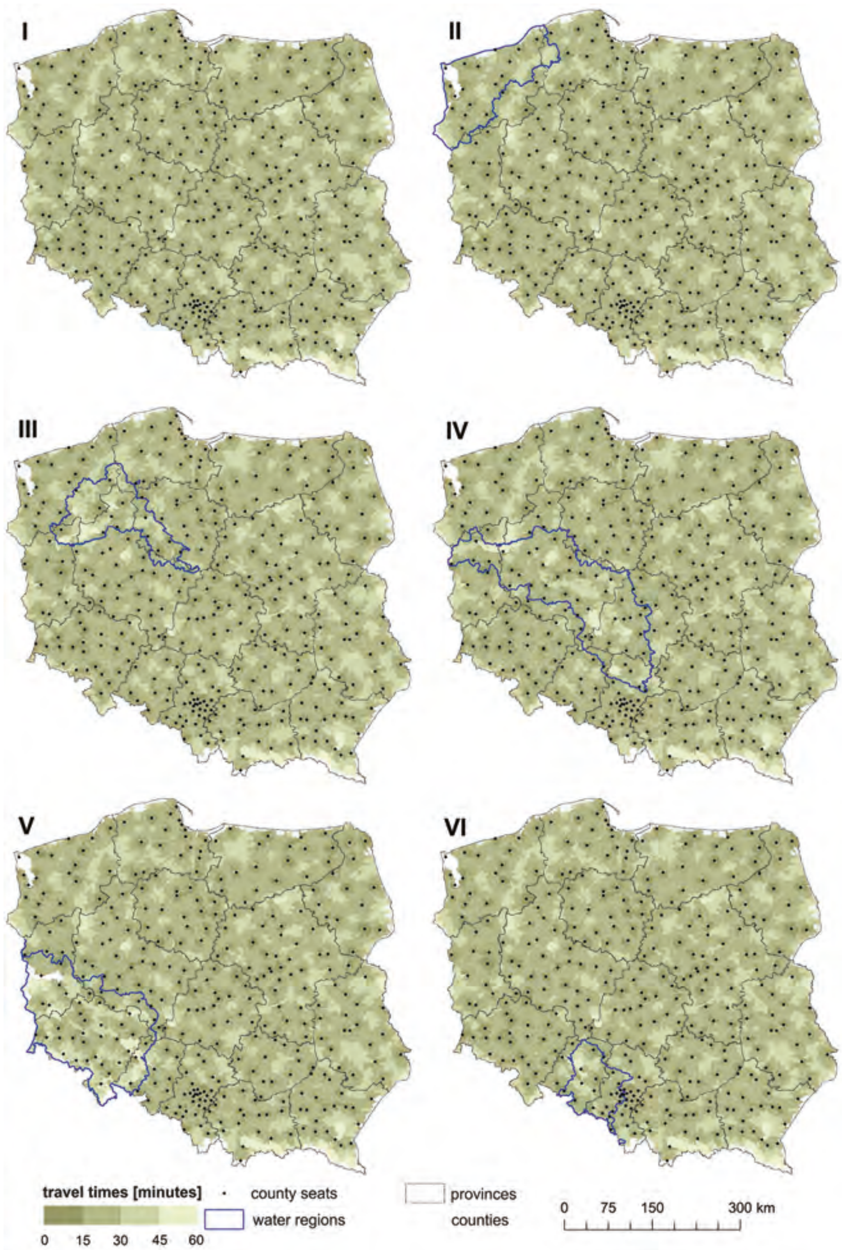
For isochronous and cumulative accessibility, the first step was to define a set of destinations (points) against which lines of identical travel time could be drawn, in line with the speed model. The first set was the centroids of the provincial capitals while the second was the centroids of the county seats. This approach to defining the points makes it possible to determine changes in temporal accessibility on a regional (accessibility to regional centres) and local (accessibility to locally significant centres) scale. For the regional scale, isochrones with an interval of between 30 and 120 minutes were drawn, while for the local scale, intervals of between 15 and 60 minutes were applied. Once the polycentric isochrones with the designated time values had been drawn, it was possible to count the facilities located in the zones within the boundaries of each isoline. Settlement units (represented by focal points) and their residents (divided by population size as follows: up to 5,000; 5,001–20,000; 20,001–50,000; 50,001–100,000; and over 100,000 residents) were aggregated. The analyses began by determining the course of the isochrones for the "normal" scenario, i.e., when there are no flood-related disruptions. Next, isolines were drawn for the road network with closed road sections inundated by floodwaters and sections "cut off" due to a flooding in adjacent segments of the road network in the different scenarios and for different spatial ranges of flooding. Figures 5.7 and 5.8 present illustrative isochrones under "normal" conditions and during a flood caused by a complete breach of stopbanks in the individual water regions within the basin of the Oder. Upon the determination of isochrones in the baseline scenario ("normal" conditions) and later for each flood scenario, the relative and absolute changes in population and settlement units within the range of each isoline were identified. Given the substantial number of flood scenarios and scopes of flooding analysed, the section presenting the results does not include cartographic representations of changes in the course of isochrones, but only tabular summaries showing the results of the simultaneous analysis of cumulative accessibility.



I – "normal" scenario, II – the Lower Oder and the coastal strip of West Pomerania, III – the Noteć, IV – the Warta, V – the Middle Oder, VI – the Upper Oder

Figure 5.7. Travel time to provincial capitals under "normal" conditions and during a flood due to a breach of stopbanks within the basin of the Oder by water region in Poland in 2019

Source: own elaboration



I – "normal" scenario, II – the Lower Oder and the coastal strip of West Pomerania, III – the Noteć, IV – the Warta, V – the Middle Oder, VI – the Upper Oder

Figure 5.8. Travel time to county seats under "normal" conditions and during a flood due to a breach of stopbanks within the basin of the Oder by water region in Poland in 2019

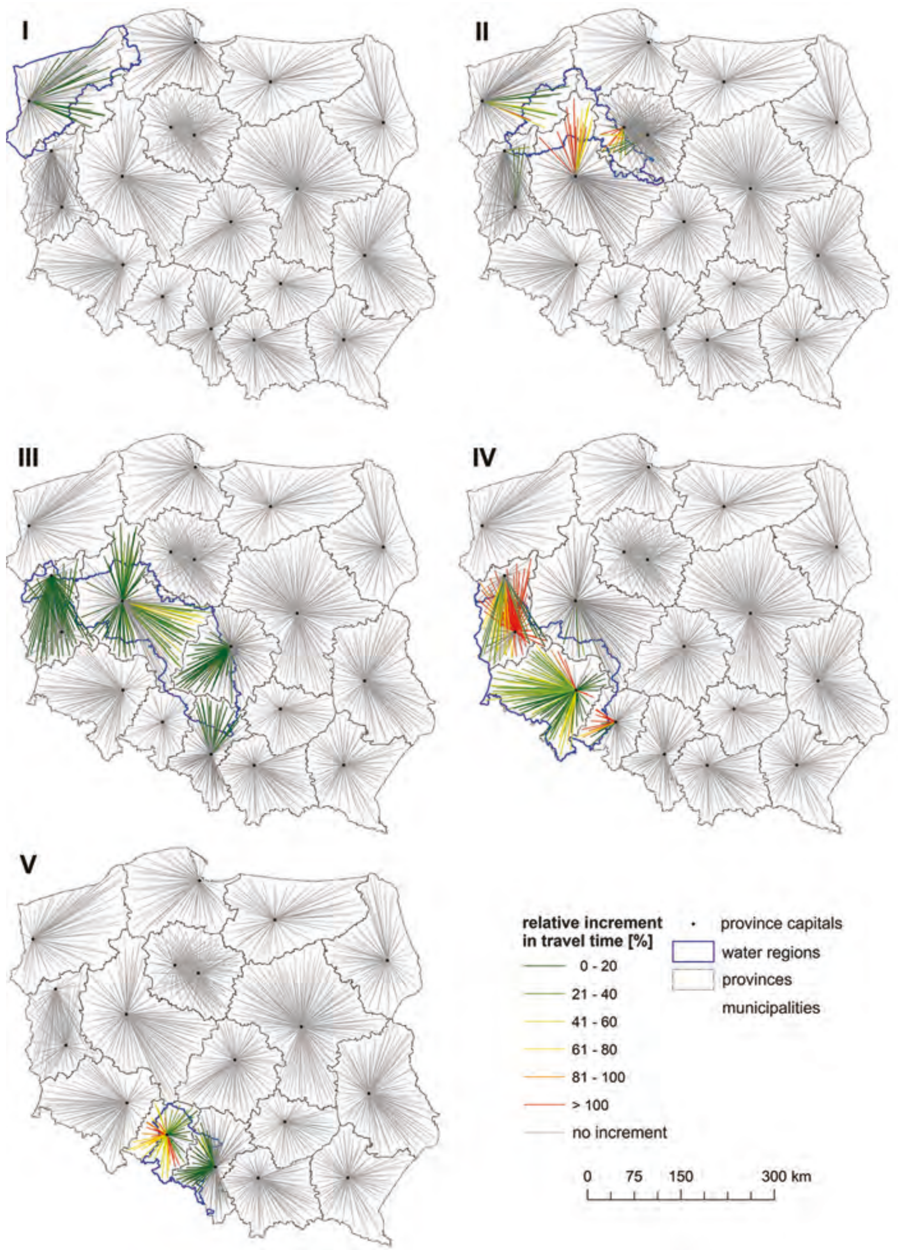
Source: own elaboration

5.2.2. Potential accessibility

The second approach selected to study the impact of flooding on the road transport system in Poland was to determine changes in potential accessibility that accompany the different scenarios of the disaster in question. It is based on measuring the possibility of interactions between a trip origin and a set of trip destinations, on the assumption that as the time or cost of a given trip increases, the attractiveness of its destination decreases (Rosik 2012, p. 24). The potential-based approach to studying transport accessibility is extremely popular since it simultaneously takes into account two components: land use and transport (Geurs and Ritsema van Eck 2001).

In the presented study, land use is represented by transport regions (municipalities) in Poland, whose weight is expressed by the population (data by the Central Statistical Office). The function of weight attractiveness is linear, while the attractiveness of a given destination (municipality) is directly proportional to its population. The weight of a transport region is a component that changes following a flood in each scenario. Subchapter 3.2.2 identifies the population of each municipality at risk of flooding in the different scenarios. As stated therein, when calculating potential accessibility by simulating the incidence of a flood with a given probability in a given water region, the weights of the affected municipalities were reduced by the population that resides in the flooded areas. This reduction is designed to synthetically reflect the decline in the attractiveness of a given transport region, where some residents, facilities and infrastructure are left outside the transport system due to flooding or being "cut-off" when roads become impassable. This also applies to the internal potential of the municipality itself.

The transport component is represented by the road network in the baseline variant and those corresponding to each analysed flood scenario. As with the method of measuring isochronous/cumulative accessibility, those sections of the road network that are flooded or "cut off" (once neighbouring sections are inundated) are removed from each scenario. Travel speed is also conditioned by the author's model. Here it must be emphasised that even though the speed model makes the analysed travel times significantly more realistic (Rosik and Śleszyński 2009, Śleszyński 2014) by reflecting the impact of congestion, the changes in traffic density on individual network sections that result from a flood and its effects differ significantly from the changes typical for recurring congestion. As a result, the speed model may underestimate drops in speed on sections that have absorbed some of the diverted traffic, while overestimating them where vehicle flows have decreased. In order to better capture these fluctuations, research needs to be conducted on a "living organism," i.e., a traffic model with appropriate parameters (Borowska-Stefańska et al. 2019a, Wiśniewski et al. 2020a). However, even this requires some simplifying assumptions to be made.



I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 5.9. Relative increments in travel time between municipalities in different provinces and their capitals following a flood due to a breach of stopbanks in the basin of the Oder by water region in Poland in 2019

Source: own elaboration

For both the entire road network and each network variant for a given flood scenario, an O-D travel time matrix was generated which covers all municipalities in Poland. By comparing the trip lengths in the baseline variant with the values obtained for the flood scenarios, the absolute and relative time increments that accompany the bypassing of the inundated areas were determined. Figure 5.9 shows an example of the relative increments in travel time between municipalities in different provinces and their capitals for the scenario with a flood caused by a breach of stopbanks in the basin of the Oder (by water region).

Disruption to the transport component also involved the internal potential of transport regions (Rosik 2009, Gutierrez et al. 2010, Salas-Olmendo et al. 2015), which is designed to reflect the importance of internal weight within the total potential accessibility of the transport region (particularly relevant for short trips). The application of the following formula for calculating travel time within a transport region (Rosik 2012):

$$t_{ii} = \frac{0{,}5\sqrt{\frac{Sur}{\pi}}}{\overline{V_{ii}}} 60$$

where:
t_{ii} – travel time within the transport region i (min),
Sur – surface area of the transport region i (km^2),
$\overline{V_{ii}}$ – average travel speed within the transport region i (km/h),

requires the average travel speed within each municipality in Poland to be determined. This was not set arbitrarily but based on the traffic speed model. For each municipality, a segment of the road network within its boundaries was selected and, based on the length of the sections and the calculated travel speed, the average value for the transport region was determined. Motorways and expressways were excluded, as they represent road classes rarely used for intra-municipal travel (e.g., they are often used as ring-roads by residents of big cities). As regards internal potential, the disruption to the transport component consists of excluding those road sections that are inundated or "cut off" in any flood scenario analysed from the entire group of sections used to calculate the average travel speed. Thus, each simulation involves a simultaneous modification of the two said components: land use and transport.

Another intrinsic element of the potential accessibility method (crucial for the results returned) is distance decay and its mathematical function. An increase in the travel time between the trip origin and destination is accompanied by a drop in its attractiveness. It is therefore imperative to determine the properties (magnitude and dynamics) of this drop. When setting parameter values that determine this property, the researcher needs to take into account the vast set of variables that describe a given trip (Geurs, Ritsema van Eck 2001, Condeço-Melhorado et al. 2013, Martinez and Viegas 2013, Östh et al. 2016).

The mathematical solution to be employed as distance decay function also needs to be selected (Spiekermann and Schürmann 2007, Rosik 2012, Spiekermann et al. 2013, Stępniak and Rosik 2018, Rosik et al. 2020). The shape typical of each distance decay function, and thus the rate of drop in the attractiveness of the destination, is selected to correspond to the length of the analysed trips. As this study focused on changes in potential accessibility for short and long trips, an exponential function was selected as its shape optimally corresponds to both (Stępniak and Rosik 2013, Rosik et al. 2015, Rosik and Stępniak 2015). Upon analysing a number of studies into distance decay published by the Institute of Geography and Spatial Organization at the Polish Academy of Sciences, the following values of β parameters were adopted: 0.034657 for short and 0.011552 for long trips (Rosik et al. 2018, Stępniak and Rosik 2018). The application of the former causes a drop in the destination attractiveness of up to 50% for a 20-minute trip (short trips: commuting to work, school, etc.), whereas the implementation of the latter brings about the same reduction for a 60-minute trip (long trips: holidays, etc.). The formula of the exponential distance decay function in potential accessibility studies is as follows:

$$f_{dd} = \exp(-\beta t_{ij})$$

where:
f_{dd} – distance decay function,
t_{ij} – travel time between municipalities i and j (min),
β – beta parameter (short trips: 0.034657; long trips: 0.011552).

The inclusion of the internal potential of transport regions and the distance decay function translates into the following potential accessibility formula:

$$A_i = W_i f_{dd}(t_{ii}) + \Sigma W_j f_{dd}(t_{ij})$$

where:
A_i – potential accessibility of the transport region i,
W_i – internal weight of a transport region i (population),
W_j – weight of a transport region j (population).

In order to identify the absolute and relative changes in potential accessibility that accompany a flood in the different scenarios, it was necessary to calculate its value in the "normal" situation for the two trip lengths in question (Figure 5.10).

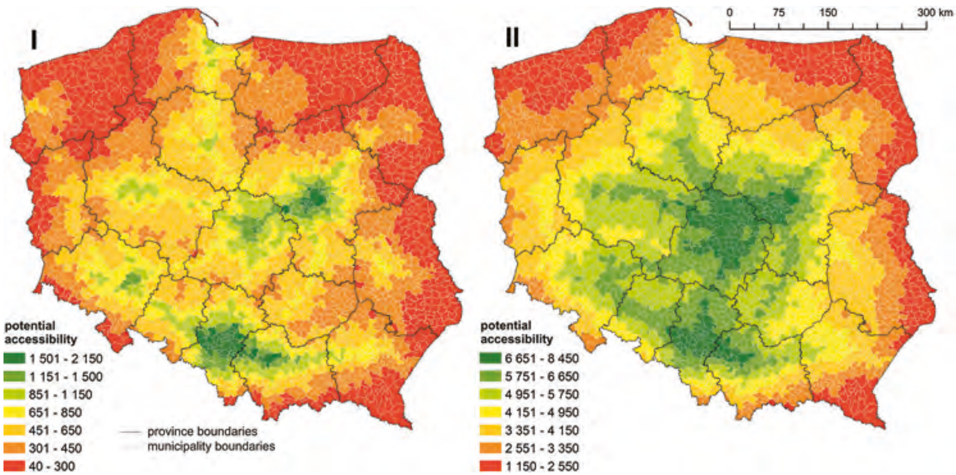


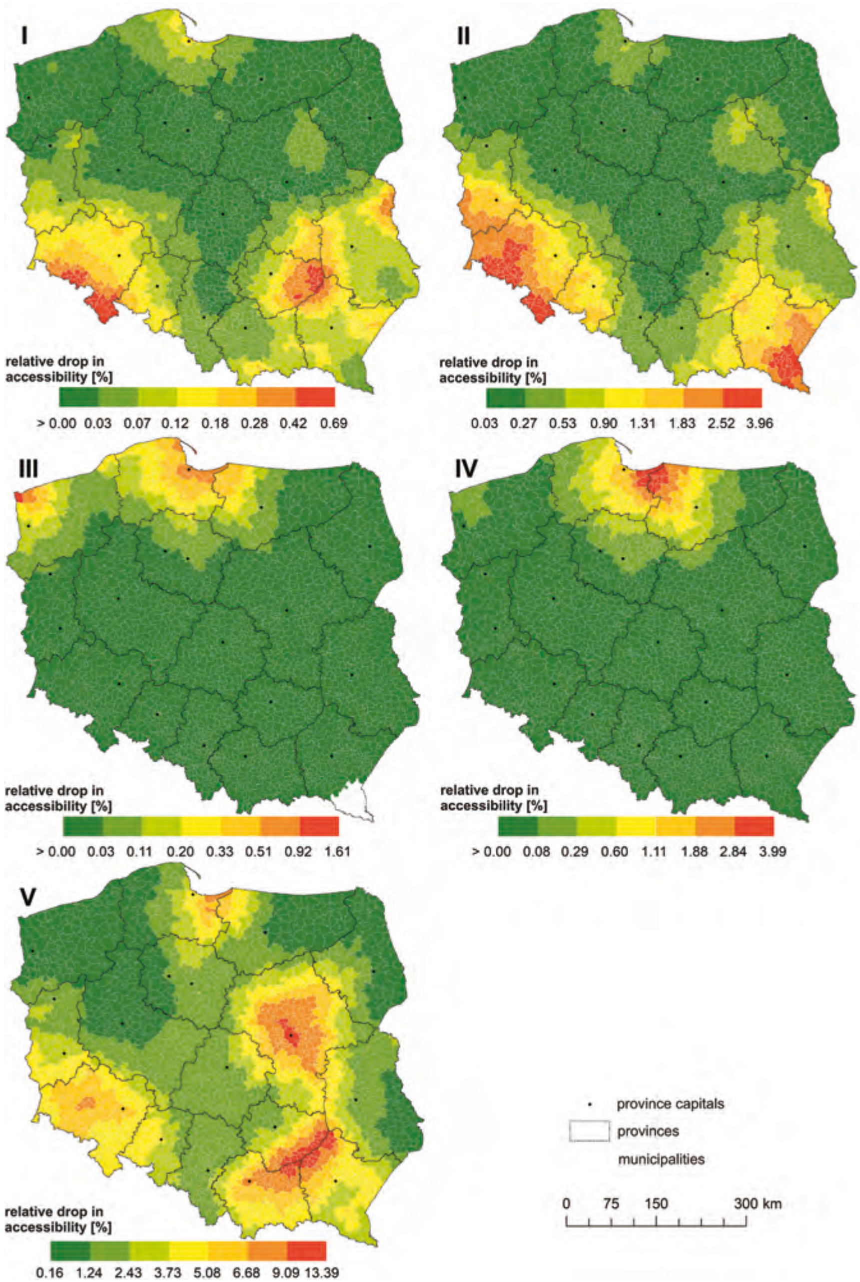
Figure 5.10. Potential accessibility of municipalities for short (I) and long (II) trips in Poland in 2019

Source: own elaboration

What emerges here is a limitation of the potential-based approach, i.e., the noticeably lower accessibility of places located at the spatial extremes of the analysed area (Geertmann and Ritsema Van Eck 1995). Once the potential accessibility was calculated (taking into account the flood-modified travel time matrices between transport regions, the modified travel times within transport regions, and the modified weights), it was possible to compare the results against the baseline variant for each respective trip length. Since the decision was made to present the results in relative terms (Rosik et al. 2012), Figures 5.11 and 5.12 show the relative changes in potential accessibility arising from the reduction in the weights of the transport regions in each flood scenario for short and long trips (no spatial differentiation of flood occurrence is included). Standardised numbers and class ranges were applied for the percentage changes in potential for the chosen trip lengths to enhance the comparability of the results. Stępniak and Rosik (2018) demonstrated the relevance of research on how the population component impacts changes in accessibility. Their study also took into account the transport component that reflected a number of infrastructure investments and the effect of different parameters of distance decay.

Unsurprisingly, relative decreases in potential accessibility are more pronounced for short trips, i.e., trips where the internal potential of a given transport region plays a significant role, thereby making the reduction of this potential more considerable. Even though the greatest drops in weights, following a breach of stopbanks, amounted to over 90% of the baseline value, they still contributed to a reduction in potential accessibility that did not even exceed 13.5%, albeit this scenario clearly had the strongest effect on accessibility, both on the number of municipalities affected by the drop and its magnitude. For short trips, the reduction in weights observed for the other flood scenarios is considerably less severe for potential accessibility – the relative drops do not exceed 4%, while there are also transport regions where no reduction was recorded whatsoever.

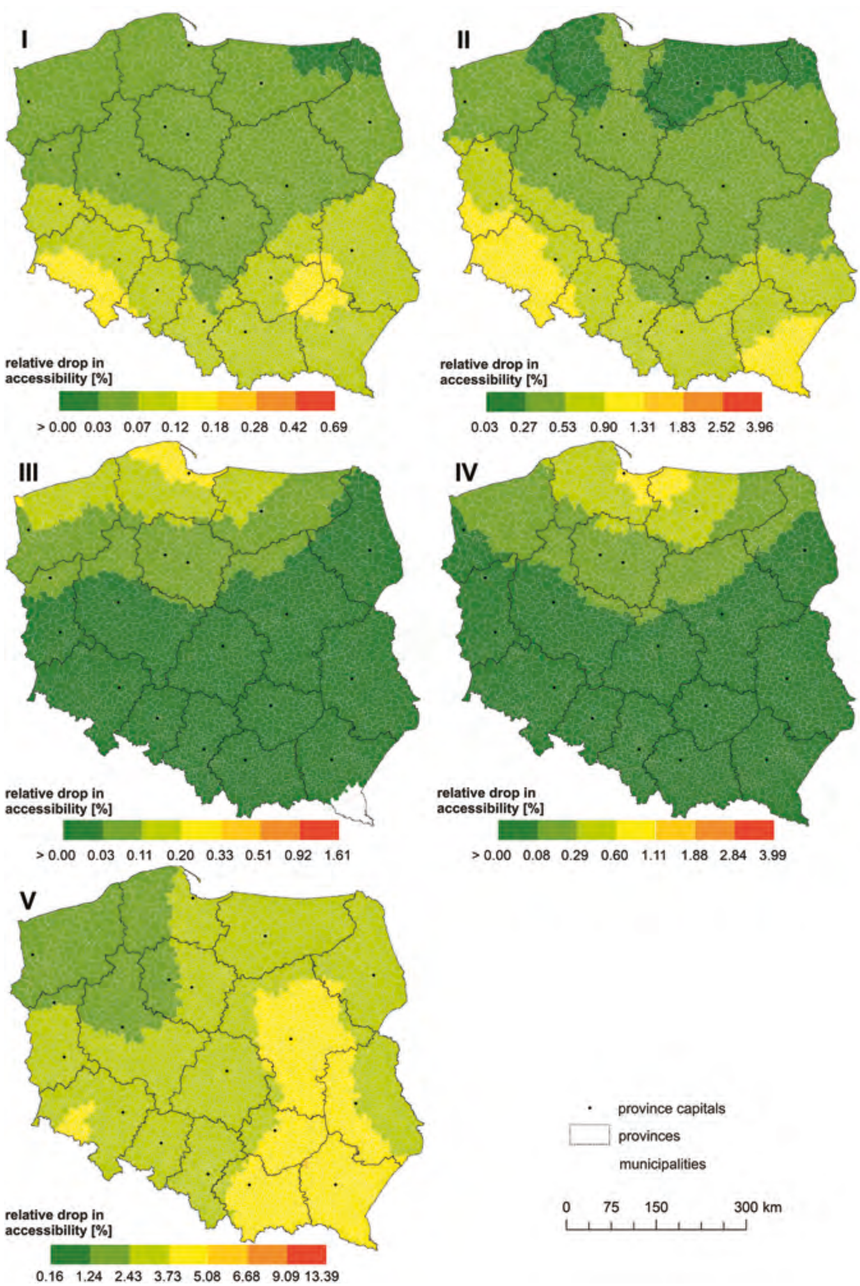
When the parameter of the distance decay function for long trips is adopted, it significantly minimises the negative effects of reducing the weights of the transport regions, leaving their spatial distribution unchanged. What becomes apparent here is the crucial role of the distance decay function, i.e., even a seemingly minor change in distance decay can return major differences in the results of the analysis. This vulnerability is sometimes considered a flaw of the potential-based approach, as is the presentation of its results without units since it can impede the interpretation of the results. Hence, relative approaches often emerge, of which the study herein is also an example.



I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 5.11. Relative drops in potential accessibility of municipalities (short trips) in different flood scenarios in Poland in 2019

Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 5.12. Relative drops in potential accessibility of municipalities (long trips) in different flood scenarios in Poland in 2019

Source: own elaboration

5.3. Road network load

5.3.1. Overview

The second approach to determining the impact of flooding on road transport was the analysis of changes in the road network load. This approach expands the results of the study based on the transport accessibility analysis by providing information on how closures of individual sections of the road network and drops in traffic generating potential can translate into changes in the volume of traffic flows and their paths. The possibility to track the volume and spatial distribution of fluctuations in the number of vehicles that appear in a specific area when simulating a given flood scenario brings more detailed data on the capability of the road transport system to respond to a non-typical event and to adapt to the disruptions it may cause (Cox et al. 2011, Berle et al. 2013). Besides diagnosing the network flexibility, this approach also verifies the importance for the entire road system of those road sections that are flooded or "cut off," presenting it as a sum of effects captured as volumes of deferred, induced or supressed traffic. In this way, the level of variability is revealed, since road sections that take over the role of other segments that are adversely affected by flooding become explicitly visible. This allows the differentiation of the possible vulnerability of the transport network to individual flood scenarios (previously determined by the transport accessibility analysis) to be made considerably more realistic.

Traffic simulation modelling,[1] which involves a number of methodological and practical approaches, is based on mathematical modelling, i.e., a set of fragmentary econometric models (Karoń and Lazarus 2010). For large areas, this modelling requires a massive amount of data on: the population (social, economic and demographic traits, travel and modal preferences, etc.), the study area (distribution of population; distribution of traffic attractors and generators; functional and spatial structure, etc.), and the transport network and its subsystems (Komar and Wołek 1994).

Traffic modelling and forecasting is a relatively recent but rapidly developing branch of science, closely related to transport system planning (Hensher and Button 2000). In the mid-20th century, two major theories on modelling trips

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[1] The main division of simulation models is by scale, with three basic scales distinguished: micro-, meso- and macro-simulations. While microsimulation models describe the behaviour of the actors within the traffic flow and the relationships between them, mesosimulation models offer a medium level of detail and no information on such relationships. Macrosimulation models (the solution employed in this study) represents traffic at a high level of data aggregation (traffic flows) and without focusing on its constituent elements (individual vehicles).

were developed: the Fratar method and the gravity model. The former is used for traffic forecasting based on multiplying a traffic matrix by a matrix of growth indices for individual transport relationships (Imamura 1989, Dybicz 2009, Junming et al. 2013, Bartuška et al. 2015). The gravity model is based on the assumption that the number of trips between transport regions is proportional to their size (population, workplaces, etc.), and inversely proportional to the distance between them. Just like with the potential accessibility method, the importance of weights as well as distance decays are determined by appropriate mathematical functions. With this method, it is possible to forecast the number of trips based on predicted changes in the factors incorporated into the modelling: demographic, employment-related, etc. (Dybicz 2009, Noulas et al. 2012, Voorhees 2013). Subsequent theories based on the division of trips into transport modes and methods of feeding trips into the network (traffic distribution) finally enabled the creation of a comprehensive traffic modelling solution called the four-step model, which is occasionally employed to study the vulnerability of transport networks (Kim and Yeo 2016). This mathematical model describes the relationships between the constituents within the structure of the supply and demand of transport and its environment, and incorporates a set of algorithms for solving specific decision-making problems in transport systems. Central to the four-step model are a supply model and a demand model (Ortuzar and Wilumsen 2001). As the name implies, the model consists of the following four steps, executed by separate mathematical models: (1) trip generation; (2) (spatial) trip distribution; (3) mode choice, i.e., distribution of transport tasks; and (4) route assignment, i.e., distribution of traffic over the transport network (Hensher and Button 2000). The first three steps represent a demand model, thus determining the transport needs pursued in a separate territorial unit broken into transport regions and transport systems located within its boundaries (Krych and Kaczkowski 2010). Modelling traffic distribution over the network is virtually impossible without specialised software (Bieńczak et al. 2014). Although other criteria are also adopted, the distribution of traffic in the four-step model is most commonly based on the assumption that network users choose routes that minimise travel times to destinations (in line with Wardrop's first principle).

Another approach to traffic simulation is agent-based modelling. The architecture of agent-based systems varies greatly, as it is tailored to the road network on which it is meant to operate. The basic unit in such solutions is the agent.

> Agents can be either single or groups of pedestrians, drivers, vehicles. An agent pursues a set goal by collecting information from the environment where it navigates. On the basis of properly integrated algorithms, knowledge and real-time data collected from the environment, agents are able to make autonomous decisions to achieve the set goal (Renkiel 2014, p. 20).

Multi-agent systems are a way to study distributed artificial intelligence (DAI) (Jękała and Michno 2004). They are used for traffic modelling and simulations. With appropriate real-time data collected by the agents from the environment, the simulation becomes more accurate. A properly designed system architecture and appropriate assignment of tasks to agents make it possible to conduct analyses for different scenarios.

The literature on traffic modelling and forecasting is abundant both abroad (Zhang et al. 1997, Teodorovic 2003, Barcelo et al. 2005, Geroliminis and Daganzo 2007, Stathopoulos et al. 2008, Fellendorf and Vortish 2010, Moretti et al. 2015, Jia et al. 2017, Fu et al. 2019, Barmpounakis and Geroliminis 2020, etc.) and in Poland (Dybicz 2001, Karoń et al. 2010, Krych et al. 2012, Bieńczak et al. 2014, Romanowska and Jamroz 2015, Dybicz et al. 2018, Żochowska and Karoń 2018, Drabicki et al. 2019, Szarata and Nosal Hoy 2019, etc.). Two Polish traffic models have so far been developed on a national scale – the 2007 National Traffic Model by the Warsaw University of Technology and the 2018 model prepared under the KoMaR Project[2] by a research team from the Institute of Geography and Spatial Organisation at the Polish Academy of Sciences, the Tadeusz Kościuszko Kraków University of Technology, and the Maria Curie-Skłodowska University in Lublin (Rosik et al. 2018). Currently, a new version of the National Traffic Model (including different modes of transport) is being developed by experts from the Warsaw University of Technology and the Tadeusz Kościuszko Kraków University of Technology.

Mobility is the relationships between a transport system and its surroundings. In transport geography, mobility is defined as the physical movement of people, objects, capital, and information on different spatial scales (Taylor 2004, Hannam et al. 2006, Cresswell 2011, Gadziński and Goras 2019). In contrast, sociologists stress that mobility can be not only physical, but also virtual or imaginary (Szerszyński and Urry 2006). Studies on spatial mobility analyse processes of territorial movement under specific geographical conditions (Nutley and Thomas 1995; Kraft 2014).

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[2] The model allows the study of vehicle traffic on a network consisting of 15 types of road sections and 2,321 internal transport regions (municipality level). The network comprises 14,069 sections covering all regional and national roads and selected sections of district and municipal roads. The speed model employed in the analyses is the product of the traffic speed model developed to date in these academic centres and the model-generated speeds obtained for the baseline simulation. The model was calibrated on the basis of the 2010 General Traffic Measurement (GTM) and takes into account six trip motivations, three obligatory: commuting to work, commuting to university/college, business travel; and three optional: shopping, visiting friends/family, and tourism.

Given the wide variability in the distances covered as regards mobility and its temporal nature (trips repeated daily or a single trip when moving house, for instance), Kaufmann (2002) structures the qualities of mobility by relating the motivations behind mobility to its two basic attributes (time and space). Thus, he distinguishes short-duration and long-duration mobility, and divides space into two types: internal to the living area and near the outside of the living area. Based on a combination of these attributes, he presents four forms of spatial mobility: daily mobility, travel, residential mobility, and migration. Daily mobility occurs within an area close to the place of residence and is of a short duration (it can be represented, inter alia, by everyday trips to work, school, shops). Travel is short-duration mobility away from the area of residence. Residential mobility refers to mobility that is long-duration, but its spatial extent is usually small. Migration is long-duration mobility away from the living area. The analyses presented in this monograph focus on the two dimensions of short-duration mobility, as they are the most common human activity where mobility choices need to be made. Primarily, these choices are binary in nature (to pursue a transport need or not). If a transport need is to be pursued, choices involve defining the following trip parameters: destination, route, timing, and mode of transport (Kruszyna 2014). The basic manifestation of short-duration spatial mobility is the movement on the transport network (which is the carrier between trip origin and destination).

Rosik et al. (2018, p. 15) state that mobility by means of personal transport often results in road network load and is conditioned by a number of factors including: the spatial structure; socio-economic and demographic properties of households; the quality of the road network; the public transport available; and the circumstances of the trip itself (motivation, etc.). Given the objective of the research presented herein (the impact of floods), it is important to focus on the effect of nature on trip choices. Among the natural factors that shape mobility, at least to some extent (excluding their impact on infrastructure), the most commonly listed are weather conditions and topographical relief. Studies on urban transport systems clearly show that users chose different modes of transport depending on the weather, where temperature and humidity, wind, insolation and precipitation are key factors (Klemm 2013). The impact of topographical relief on the modal split and mobility usually depends on the traits of the user (age, health, etc.) and their transport needs. However, the relevance of the majority of the natural factors for mobility is also determined by the socio-political climate (Radzimski 2012). Pro-environmental societies where the political climate favours low-emission transport solutions do not find the impact of natural factors unusual and thus it is not a stress-inducing phenomenon there. Therefore, the non-typical event analysed in this monograph can be assigned to three of the groups of factors shaping mobility described above. This is because it can affect relationships between the potentials of traffic generation and attraction, it can impact the condition of the road network, and it can undoubtedly change the circumstances of the trip itself.

In order to determine how the combination of these mobility-modifying factors (here: different flood scenarios on different parts of the road network) translates into changes in the road network load. The study involved a series of simulations of changes in the distribution of traffic in the pursuit of two obligatory motivations: commuting to work and business trips. These were selected specifically because they are obligatory and represent trips of different lengths (commuting – short trips; business travel – long trips), corresponding to the potential accessibility analyses. The assumption was made that, unlike for optional trips (visiting friends/relatives or tourism), cancelling journeys for commuting and business trips would account for a small percentage of the decisions made by road network users in the event of an additional factor reinforcing distance decay (here: a flood). In the short-term perspective (which is the case during a flood), there would also be no change in trip destinations for these motivations (travelling to a different company office or changing one's job are highly unlikely in such circumstances). Given the invariability of the modal split, the road user can only change either the departure time or the route. The incorporation of commuting into the analysis is further justified by the fact that it is the most significant trip motivation (Pilot Study... 2015).

The research procedure began with the adaptation of the road network database to the requirements of the process of traffic distribution. Given the principles of how the software application employed works (see: Subchapter 5.3.5), it was required to assign to each road segment (on top of attributes related to traffic speed modelling) an identification number for its start and end node, which provided information on their connection with subsequent segments of the road network. Next, it was necessary to determine the speed of free-flow vehicle traffic (V_0), i.e., the speed that should not be exceeded on a given section between nodes (Szczuraszek 2009, Szczuraszek and Chmielewski 2017), and the model capacity of a given section, which defines the pre-determined number of passenger cars that travel along this road section in one direction per unit of time (Q_{max}). As for capacity, the values provided by Szczuraszek and Chmielewski (2017) were adopted, as shown in Table 5.2. As regards speed, the V_0 values listed by these authors were discarded, and the values obtained from the speed model were applied instead, bearing in mind that they were mostly the product of the baseline free-flow traffic speeds reduced by different factors acting within the road network.

The speeds thus determined were then modified by the volume of vehicle traffic. As the volume increases on a given section of the network, the speed at which vehicles travel along it decreases (Kieć et al. 2012). To determine the magnitude and the pace at which this volume would reduce speed, it was necessary to introduce a section decay function. For this purpose, one of the most popular decay functions, i.e., the Bureau of Public Roads Function, was applied, as it takes into account the travel time along the section under free-flow traffic conditions, the volume of traffic on the section and its capacity (Dybicz 2009). The function is as follows:

$$t_{cur} = t_0 \cdot (1 + \mathrm{a} \cdot sat^b)$$

where:

$$sat = \frac{Q}{c \cdot Q_{max}}$$

t_{cur} – travel time along the section loaded by traffic volume Q,
t_0 – travel time along the section under free-flow traffic conditions,
Q – traffic volume [veh/h],
Q_{max} – capacity [veh/h],
a, b, c – parameters.

In order to determine the travel time along the section loaded by a given traffic volume (and thus the V_{cur} speed), it is necessary to take into account three function parameters (a, b, c). As the method of selecting capacity values for a network section took into account, to a certain extent, the traffic volume related to the density of development in the vicinity of the section, the decision was made to implement the parameters applied in the KoMaR Project[3] (Rosik et al. 2018, p. 72), and to discard the default values from the Visum software. The authors of the KoMaR Project adopted parameters that brought a relatively small increase in travel time, as the procedure they employed to determine speeds in free-flow traffic indirectly took into account the factor of population in the vicinity of a given road section (Rosik et al. 2018, pp. 64–74). The implementation of the Bureau of Public Roads Function in the software brought a reduction in the travel speed along a given network section at successive iterations.

5.3.2. Trip generation

Once the road network and its parameters imperative for the subsequent distribution of traffic had been prepared, it was possible to implement the next stages in line with the four-step approach. The first is trip generation, i.e., the phase

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[3] For motorways, the parameters established in the KoMaR Project for the MW road class were adopted, for dual-carriageway expressways – EW2, for single-carriageway expressways – EW1, for dual-carriageway national roads – NR2, for single-carriageway national roads – NR1, for dual-carriageway regional roads – RR2, for single-carriageway regional, district, municipal and other roads – RR1.

when it is necessary to answer the question of what prompts users to make a trip (motivation). Two motivations were addressed in the study: commuting to work and business trips, thus making it necessary to determine the traffic potential for each (traffic generation and attraction). The most common trip motivation model is the linear regression model (multivariate/multiple regression models) (Bieńczak et al. 2014). For traffic generation, it is most commonly the demographic and socio-economic characteristics of the population within the transport region area; for attraction, it is the properties of land use and development. As regards commuting to work, this could be the number of employed persons (Figure 5.13), jobs, or businesses (Żochowska et al. 2016).

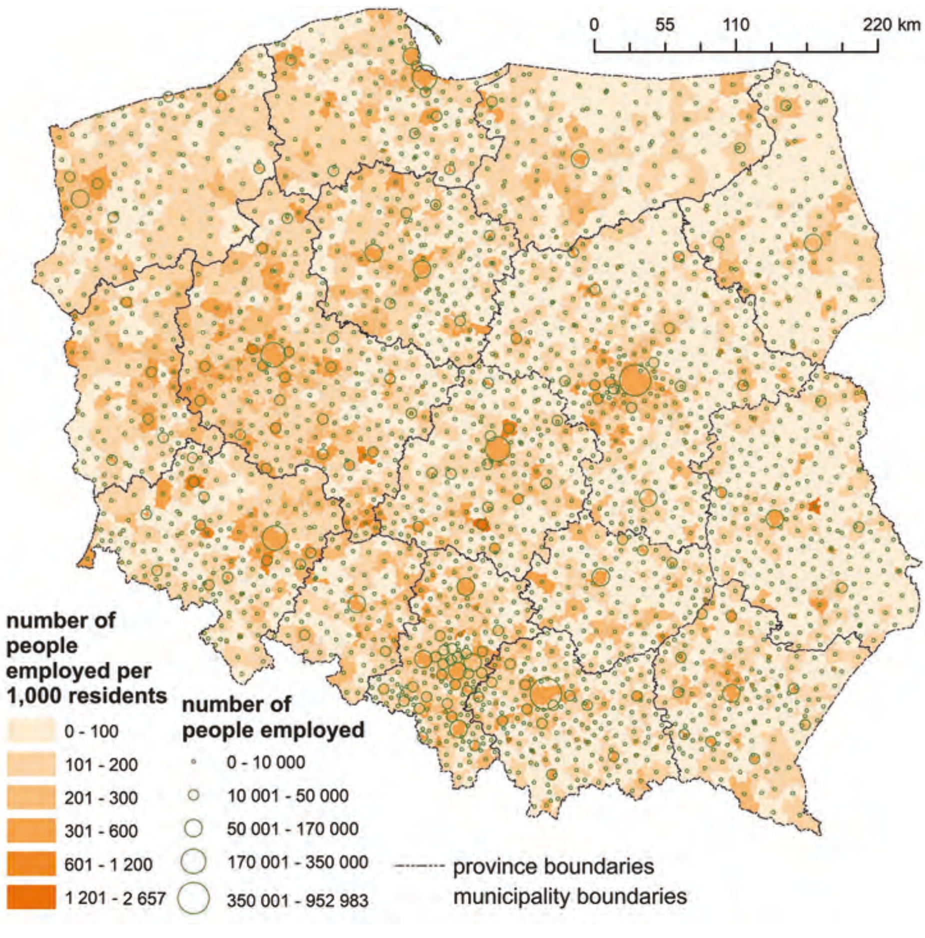


Figure 5.13. The number of people employed and the number of people employed per 1,000 inhabitants by municipality in Poland in 2018

Source: own elaboration based on data from the Local Data Bank (Central Statistical Office, 2018)

For commuting, however, the presented study employs a solution based on actual data on employment-related mobility, rather than model-generated figures. For this purpose, the data published by the Central Statistical Office on commuting to work in 2016 was used, derived from the official sources of the Ministry of Finance, and the Social Insurance Institution. This data included both flows between municipalities within a given province and to municipalities in other provinces (Population Flows... 2019). The datasets provided by the Central Statistical Office include information on the number of people who travel to work between a given pair of municipalities (the municipality of residence and the municipality of employment). The report published by the Central Statistical Office (Population flows... 2019) indicates that 3,273,515 people commuted to work in 2016. Chojnacki (1961) defines a "flow" as a measure representing the quantity of goods or the number of people moved from a given trip origin to destination without specifying the route. Thus, this concept must not be confused with the term "transport," where the route is explicitly defined (Potrykowski and Taylor 1982). The contextualisation of the term "trip" in relation to the two concepts above seems relatively simple, since a "trip" here is any movement motivated by commuting to work between a given origin and destination, involving one or more "transfers" (Lijewski 1967). In this context, a "transfer" is any part of the trip that takes place using a single mode of transport. A "trip origin" is the place where the trip begins, while a "trip destination" is the place where the trip ends. Any trip results in traffic on the transport network, and the basic measures of this are "traffic volume" and "traffic density" (Kaczkowski and Krych, 2010).

When the number of residents of working age per municipality is taken into account to interpret the data on people leaving a municipality or coming to a municipality for work (Figure 5.14), it clearly confirms that high traffic attraction potentials are mainly observed in large cities, while neighbouring municipalities boast high traffic generating potentials for this motivation.

On average, people coming to work from outside a municipality constitute nearly 6% of its working-age population. By far the highest percentages are observed in the municipalities of Kleszczów (Bełchatów District), Puchaczów (Łęczna District), Kobierzyce (Wrocław District), Tarnowo Podgórne (Poznań District) and Polkowice (Polkowice District). The percentage of those leaving a municipality for work on average exceeds 12% but is particularly low for Krynica Morska and Świnoujście. This phenomenon is also clearly reflected in the ratio between the number of people coming to work in a given municipality and those leaving for work outside of it (Figure 5.15). The predominance of settlement units with a negative balance in this respect is evident mostly in eastern Poland, where the prevalence of those going to work outside the municipality is significantly higher. Municipalities that are particularly attractive to workers are provincial capitals and those municipalities with specific labour market conditions (e.g., Kleszczów and its special economic zone).

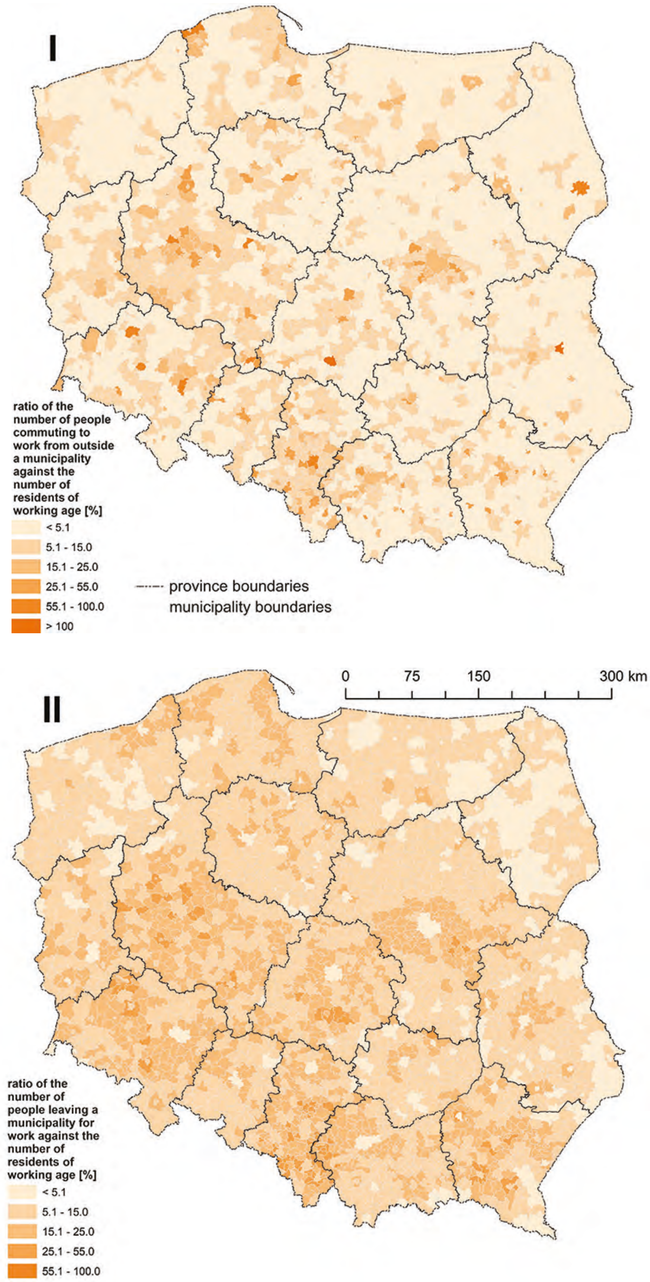


Figure 5.14. The percentage ratio of the number of people commuting to work from outside a municipality (I) and leaving a municipality for work (II) against the number of residents of working age in the municipality in Poland in 2016

Source: own elaboration based on data from the Central Statistical Office (2019) and the Local Data Bank (Central Statistical Office, 2016)

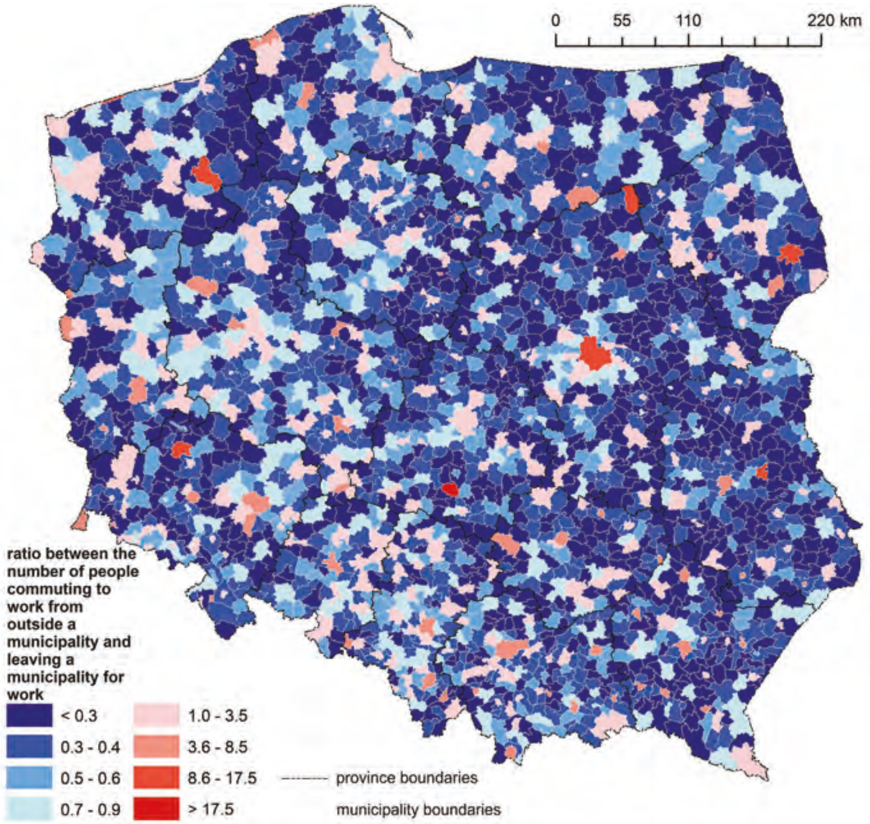


Figure 5.15. Disparity between the number of people commuting to work from outside a municipality and leaving a municipality for work in Poland in 2016

Source: own compilation based on data from the Central Statistical Office (2019)

According to the database of the Central Statistical Office on commuting to work (which lists individual relationships and only takes into account movements of at least ten people), there are 2,867,186 commuters (in 34,986 relationships), which means that the difference against the total number amounts to 12.4%. The previous survey by the Central Statistical Office (2011) showed a difference of 12.6% (Commuting to work, 2014). Mobility between rural areas and cities in urban-rural municipalities pertain to fewer than 8% of the commuting population and just over 3% of relationships. When the assumptions of the KoMaR Project were taken into account, i.e., trips lasting over two hours should be excluded from the compilation on commuting (they are seen as trips to visit relatives/friends – it is assumed that most people who would have to commute for over 120 minutes usually decide to live in the municipality of their workplace and only travel home at weekends; Rosik et al. 2018, p. 105), the reduction that pertained just to trips that last over 120 minutes in 2016 decreased the number of commuters by 4.5%, and the number of relationships by 10.7% (on the assumption that the travel time by car is determined using the traffic speed model).

Since no matrix data is available for business trips, it was necessary to determine the traffic generating potentials by identifying their determinants. In the only nationwide traffic model to date that considers determinants on the municipal scale (Rosik et al. 2018), the number of companies and commercial law partnerships is given as a variable representing the potential of traffic generation and attraction for this motivation (Figure 5.16).

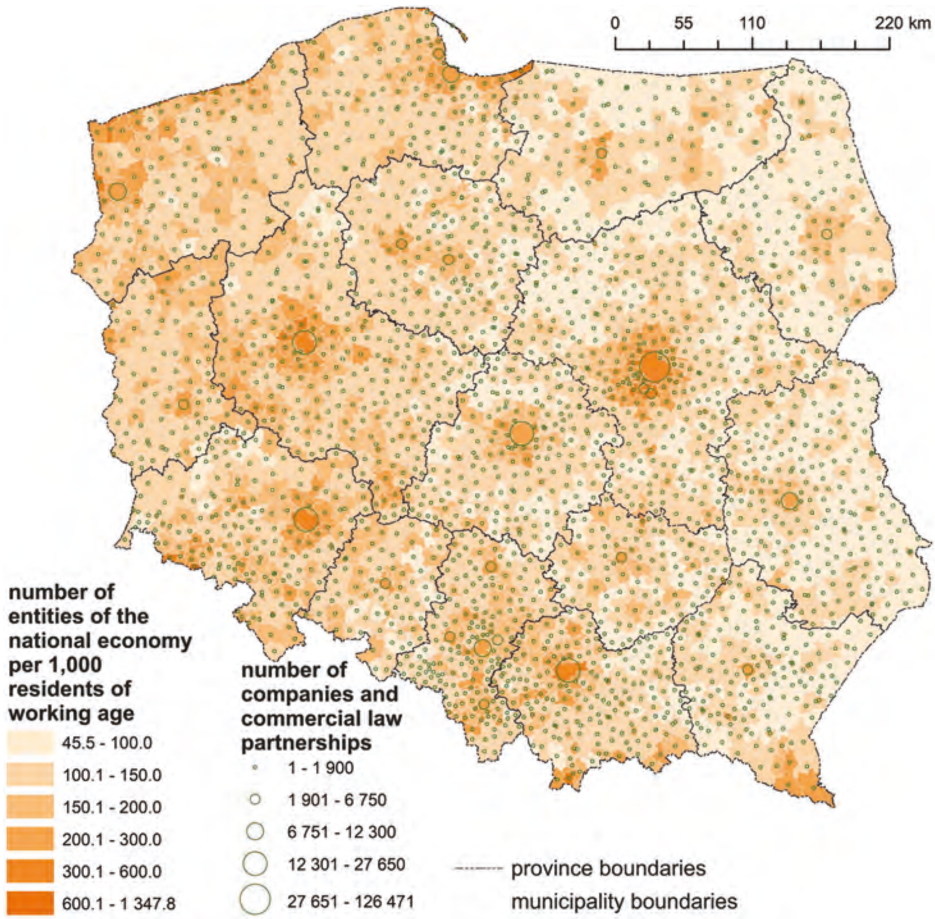


Figure 5.16. The number of entities of the national economy per 1,000 residents of working age in a municipality and the number of companies and commercial law partnerships in municipalities in Poland in 2018

Source: own elaboration based on data from the Local Data Bank (Central Statistical Office, 2018)

Here, the concentration of potential in the largest cities is even more pronounced than for commuting. On the national scale, this causes a massive disparity – for the average of 198, the standard deviation exceeds 2,700. The enormous disproportion in the spatial distribution of the analysed phenomenon is also evident. In the majority of municipalities the number of companies and commercial law partnerships ranges from lower single digits to double digits, while in regional capitals it may amount to tens of thousands. Warsaw is unrivalled here, which results in the generation of vehicle traffic incomparable to anywhere else in Poland when combined with the relatively low distance decay for this motivation in the transport region. This potency is even more noticeable when only the largest (by employment) entities of the national economy are considered (Figure 5.17). Given the significantly reduced number of municipalities where these entities carry out their business, it is evident between which transport regions the greatest volumes of business-related traffic occur.

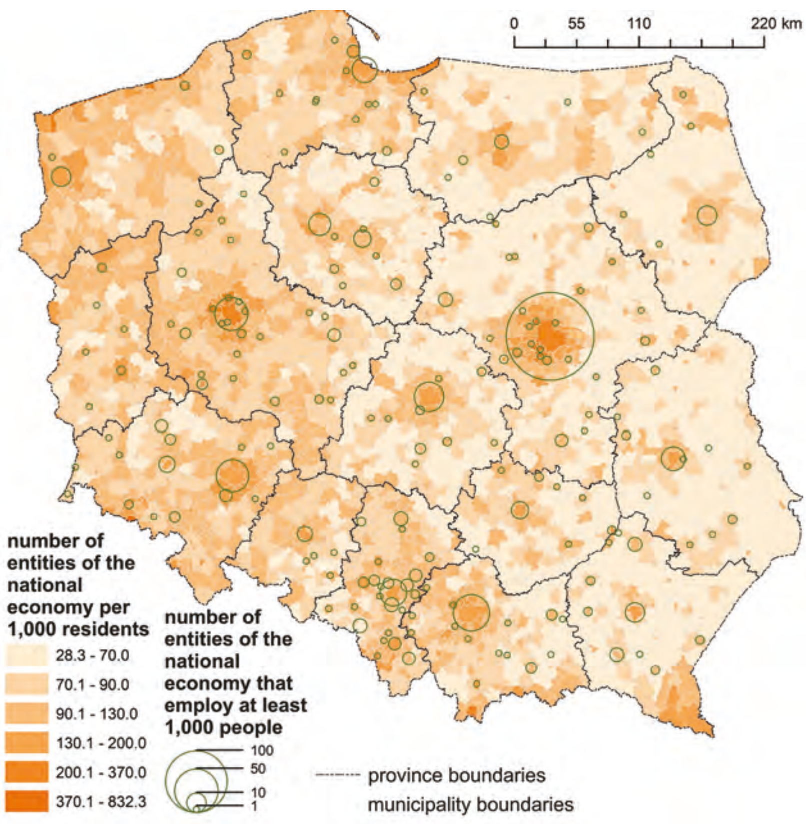
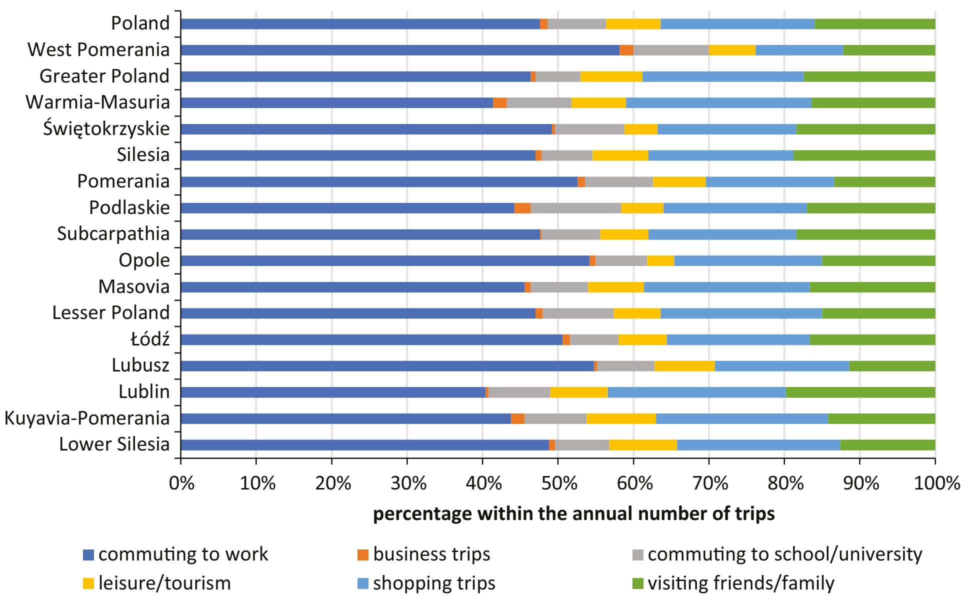


Figure 5.17. The number of entities of the national economy with 1,000 or more employees and the number of entities of the national economy per 1,000 residents in a municipality in Poland in 2018

Source: own elaboration based on data from the Local Data Bank (Central Statistical Office, 2018)

To understand traffic generation, it is also important to comprehend what percentage of the total number of trips in Poland is attributable to the motivations under study. Empirical observations are the basis for all modelling (including traffic modelling), and traffic simulation modelling employs quantitative data (the number and type of vehicles recorded at points located within the transport network; social surveys on residents' mobility, etc.). In Poland, these are collected periodically as part of the General Traffic Census, the Comprehensive Traffic Analysis and other relevant surveys, including the Pilot Study of Transport Behaviour of the Population in Poland conducted by the Central Statistical Office (2015), which shows that commuting to work accounts for as many as 48% of trips taken in Poland for all motivations, and the regional variation expressed by the standard deviation is 4.8 percentage points. Business trips, on the other hand, are by far the least frequent motivation (1% of all trips) (Figure 5.18).



The Pilot Study of Transport Behaviour of the Population in Poland (2015) took into account one more motivation: returning home from work. For the purposes of the study presented herein, this motivation was incorporated into other motivations by duplicating their results, e.g., commuting to work also included returning home from work. According to Rosik et al. (2018), leisure-related motivation included, inter alia, tourism, while visiting friends/family was represented by personal matters in the survey by the Central Statistical Office

Figure 5.18. The percentage of the annual number of trips by motivation in Poland in 2015

Source: own elaboration based on data from the Central Statistical Office (2015)

In 2015, the average number of trips per capita in Poland amounted to 422, of which as many as 200 were for commuting to work and only 4 were business trips (Figure 5.19). The latter were sporadic and required a significantly longer average distance to be covered.

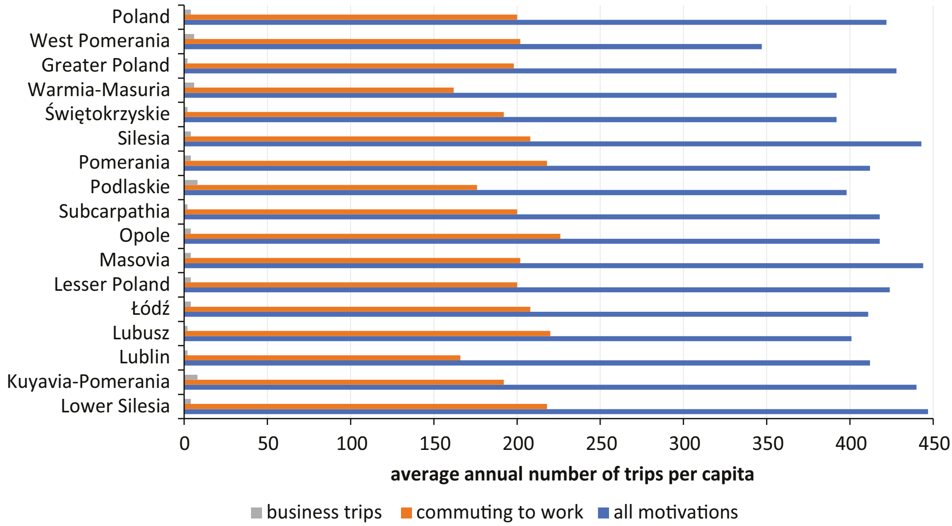


Figure 5.19. The average annual number of trips – commuting to work, business trips, and all motivations – per capita in Poland in 2015

Source: own elaboration based on data from the Central Statistical Office (2015)

In order to compare the results obtained in the subsequent traffic simulation stages, the total volumes of the weights of potentials for the two motivations (commuting and business trips) were standardised following the procedure applied in the KoMaR Project.

5.3.3. Spatial distribution of trips and classification of transport tasks

The second step to be discussed is the spatial trip distribution, i.e., the distribution of traffic generating potentials between pairs of transport regions (origins and destinations). The result is a travel matrix, also called the origin-destination matrix (O-D matrix), whose size corresponds to the number of transport regions and whose graphical expression is the structure of traffic. The matrix reflecting the number of commuters was included in the data from the Central Statistical Office. This matrix only needed to be "cleaned" of all values that represented the aforementioned travel time limit of over 120 minutes. When the number of commuters for this relationship was assigned to individual inter-municipal relationships, a graphic structure of traffic was constructed for this motivation (Figure 5.20).

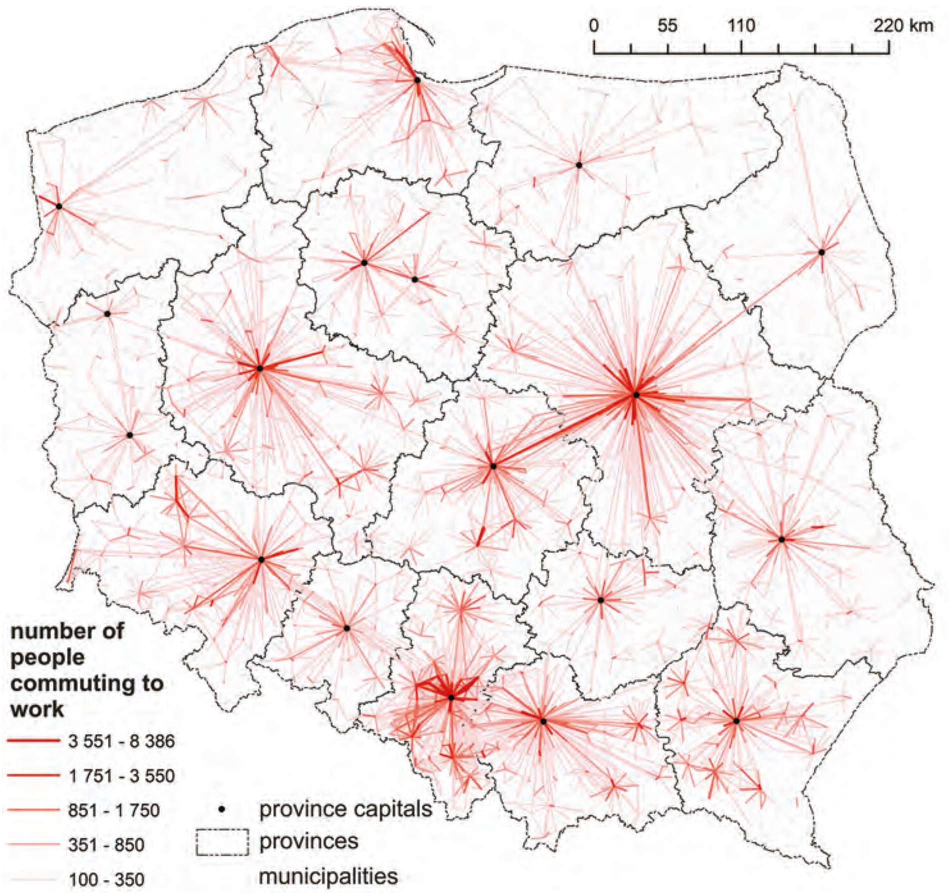


Figure 5.20. The number of people commuting to work in Poland in 2016 (excluding movements of fewer than 100 people or lasting over 120 minutes; on the assumption that the means of transport is passenger car)
Source: own elaboration based on data from the Central Statistical Office (2019)

For over 62% of inter-municipal relationships and nearly 75% of commuters, the travel time does not exceed 30 minutes. When the travel time is extended to 60 minutes, it expands that relationship by almost another 25 percentage points and the population percentage by almost 18 (Figure 5.21).

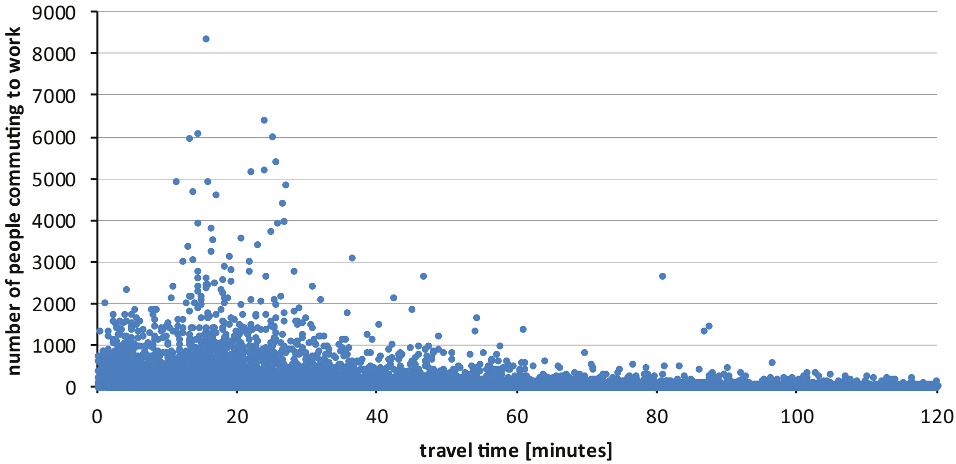


Figure 5.21. The number of people commuting to work in Poland in 2016 against the travel time by passenger car

Source: own elaboration based on data from the Central Statistical Office (2019)

It must be noted that some results obtained give a distorted picture of the phenomenon due to the way the source data is presented. Travel times between municipalities (or more precisely, between the points that represent them) are shown here without taking into account the actual places of residence and employment, and trips within municipalities are not included (apart from the division into rural areas and towns within urban-rural municipalities). Many of these trips, however, may last considerably longer than those that require crossing a border between municipalities, for instance. The pilot study by the Central Statistical Office reveals that the average travel time to work in Poland ranged from 19 to 31 minutes in 2015 (Figure 5.22).

For business trips, no such "convenient" data was available, so it was necessary to apply the classical gravity model, in which a certain number of trips are made between two transport regions along the shortest path connecting the centroids that represent them (Rudnicki 2014):

$$T_{ij} = \frac{G_i A_j f_{ij}(L_{ij})}{\sum A_j f_{ij}(L_{ij})}$$

where:

T_{ij} – the number of trips that begin in region *i* and end in region *j*;
G_i – number of trips generated in the origin region *i*;
A_j – number of trips absorbed in the destination region *j*;
f_{ij} – the value of the decay function for the relationship between regions *i* and *j*;
L_{ij} – the distance (length) between regions *i* and *j*.

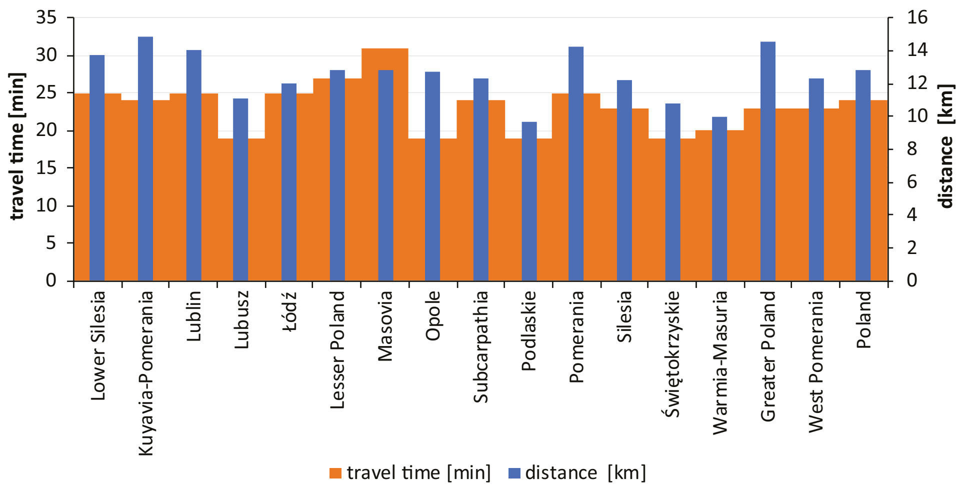


Figure 5.22. The average travel time and distance for commuting to work in Poland in 2015

Source: own elaboration based on data from the Central Statistical Office (2015)

The number of trips increases along with the volume of traffic generating potentials and decreases with the distance decay function. For business trips, Rosik et al. (2018) determined a distance decay of $\beta = 0.046210$, the application of which results in a 50% reduction in the attractiveness of the destination for a trip that lasts over 15 minutes.[4]

It is challenging enough to determine the parameters of the distance decay function, even for the scenario where the trip takes place under "normal" conditions (these parameters reflect the number of typical factors that can affect how attractive a given trip destination is perceived to be), so quantifying the impact that non-typical events (e.g., natural disasters) have on the magnitude and dynamics of a decrease in the appeal of a given attraction that generates traffic for a given trip motivation seems even more formidable. Even if one assumes that some (e.g., optional) trips will not be cancelled at the traffic generation phase, specific determinants (extremely bad weather, etc.) may still discourage people from travelling to reach particular destinations. For instance, the frequency of short-distance trips to a local grocery shop will not decrease as dramatically as to shopping centres. Despite the richer retail offer and attractiveness of the latter (being also places of recreation), significantly increasing the time customers

[4] The choice of the parameter for the distance decay function was based on the fit of the model (the coefficient of determination – R^2), which for business trips amounted to 0.62 in the KoMaR Project (Rosik et al. 2018, p. 132).

are willing to spend travelling to reach them, in the event of particularly unfavourable traffic conditions these facilities may then lose their appeal. A very important factor affecting the choices made by trip takers and their willingness to make a trip if a non-typical event occurs is the dynamics of the disturbance itself – whether it allows the opportunity to prepare for the new circumstances or forces a reaction to processes already taking place.

The third step is the modal split, i.e., determining the percentage for different means of transport. Here, there is a primary split, conducted at the trip generation phase, and a secondary split, following the spatial distribution of trips, which is the result of the many different factors that the trip taker takes into account (distance, travel time, etc.). How individual road network users choose a mode of transport is a complex issue that depends on, amongst others: access to a passenger car and/or public transport; household income; perception of convenience; trip motivation; transport behaviour. Determining how a mode of transport is chosen is the basis for dimensioning transport networks (density and capacity of the street network and the network of bus/tram lines, etc.) and for shaping transport behaviour, e.g., implementation of car-use restrictions (Fierek and Zak 2012, Bieńczak et al. 2015, Sawicki et al. 2016). As the entire study focuses on vehicular transport, it was necessary to determine what percentage of commuting and business trips are made by passenger car. As indicated by the results of the Pilot Study... (2015) by the Central Statistical Office, a passenger car is used to commute to work/school by nearly 75% of respondents at least five times a week. On a regional basis, the residents of south-western Poland are particularly likely to travel by car (Figure 5.23).

Jamroz et al. (2014) show that 88% of the transport tasks expressed in passenger-kilometres within the total land transport in Poland was performed by car. The survey by the Central Statistical Office shows that the percentage of trips to work made by passenger car ranges from 57.4% for Masovian Province to 74.6% for Subcarpathian Province. This differentiation was incorporated in the modal split applied, which took into account the province of residence of the person travelling to work.[5] As for business trips, a fixed value of 70.0% was applied, since there was no precisely specified value for the percentage of passenger cars for this motivation in the data by the Central Statistical Office, and because this percentage differs significantly due to the specific purpose/nature of such trips (as indicated by Rosik et al. 2018).

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[5] Greater Poland – 64.1%, Kuyavia-Pomerania – 61.4%, Lesser Poland – 61.7%, Lower Silesia – 66.4%, Lublin – 61.6%, Lubusz – 70.0%, Łódź – 62.7%, Masovia – 57.4%, Opole – 69.3%, Podlaskie – 60.9%, Pomerania – 58.5%, Silesia – 67.9%, Subcarpathia – 74.6%, Świętokrzyskie – 70.4%, Warmia-Masuria – 63.1%, West Pomerania – 60.9% (Pilot Study… 2015).

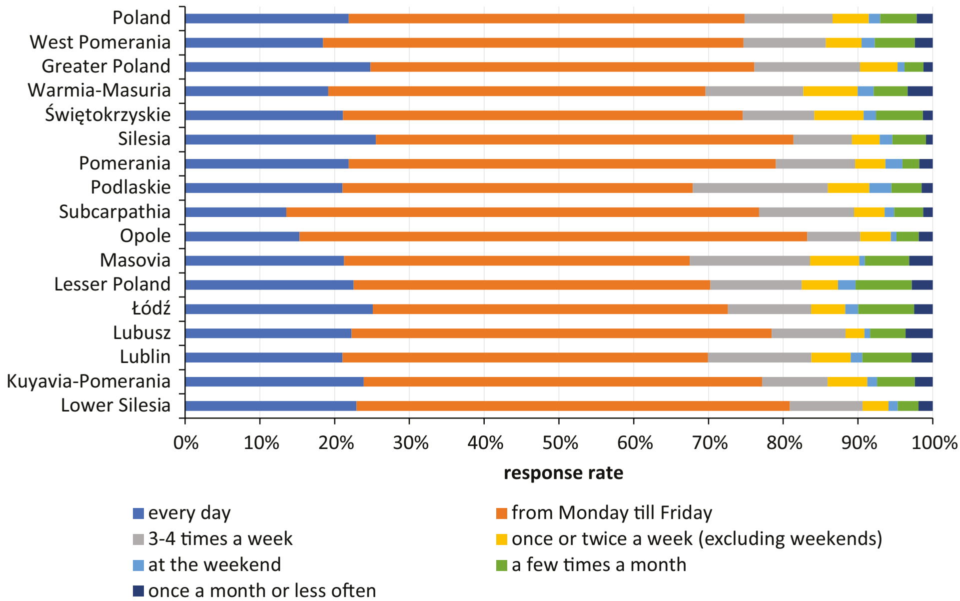


Figure 5.23. The percentage of passenger car use to commute to work/school in Poland in 2015

Source: own elaboration based on data from the Central Statistical Office (2015)

As regards vehicle occupancy for passenger cars, it was assumed to be 1.5 persons per vehicle. This value was not spatially differentiated but applied directly to the two motivations in question. A review of the studies on the issue of the average number of people travelling in a single car indicates a certain diversity for this variable. For instance, The Transport Prognostic Model of Trips for the Metropolitan Area as part of The Metropolitan Area Transport and Mobility Strategy for the Tri-City of Gdańsk-Gdynia-Sopot to 2030 (2015) predicted vehicle occupancy in 2020 separately for trips made by residents within the Tri-City (1.42) and outside it (1.58). The Gdańsk Traffic Study (2016) indicates that the average vehicle occupancy of a passenger car is actually 1.5 persons. The same value was adopted in the KoMaR Project (based on 2008 data), while The Concept for the Integration of Transport Systems in the Kraków Metropolitan Area (2017) states that the vehicle occupancy there amounts to 1.3 persons per car. Pilot Study... (2015) also addressed the issue of vehicle occupancy (defined therein as the "number of persons travelling in a vehicle including the driver"). The section with the results of Pilot Study… does not refer directly to this variable, but in a separate publication that contains conclusions to the study, entitled Methodological Principles of the Population Mobility Survey (2015), the authors stress significant flaws in the manner this type of data is collected.

5.3.4. Traffic distribution over the network

The final step is traffic distribution over the road network, i.e., identifying the routes selected by road network users to travel from origins to destinations. The number of vehicles (passengers) that burden a given section of the transport network (road, street, public transport route, etc.) is determined. Understanding traffic distribution makes it possible to select a particular type of intersection or grade-separated junction to be built; to appropriately dimension elements of a given road; to design traffic organisation; to assess traffic conditions; and to design road infrastructure so that it can accommodate traffic that may appear in the future. The assumptions made in the research project (whose results are presented in this monograph) involved traffic distribution over the network without calibration, since this task would be so complex that it would need to be the subject of another research project (vide: the KoMaR Project). One challenge here is how dynamically the system becomes disrupted after the occurrence of a natural disaster. Another issue stems from the episodic nature of natural disasters when in light of the constant improvements to the transport system and its surroundings. This may render any observations made during previous irregular disruptive episodes somewhat irrelevant when trying to model the future behaviour of road users.

The distribution of traffic generated by commuting and business trips over the road network (Figure 5.24) gives a good indication of the nature of these trips when made by passenger car. A rise in the trip length increases the importance of roads that have the highest parameters, i.e., motorways and expressways.

The differentiation of trip lengths is also clearly illustrated by the juxtaposition of annual passenger car mileages by trip motivation (Figure 5.25). What becomes apparent is the very high share of vehicle-kilometres for commuting. Naturally, the largest traffic flows for commuting in Poland occur for relatively short distances, i.e., when travel time is under 30 minutes. Although business trips are generally made over longer distances, their frequency is considerably lower, which translates into an incomparably lower percentage of kilometres travelled by passenger cars for this motivation. In total, the trips under study account for slightly over 65% of the total annual passenger car mileage in Poland (Figure 5.26) (Pilot study... 2015). For commuting, on average almost half of all kilometres that cars travel in Poland are trips of up to 20 km (Figure 5.27). For business trips, 56% of the kilometres travelled are related to covering distances longer than 100 km.

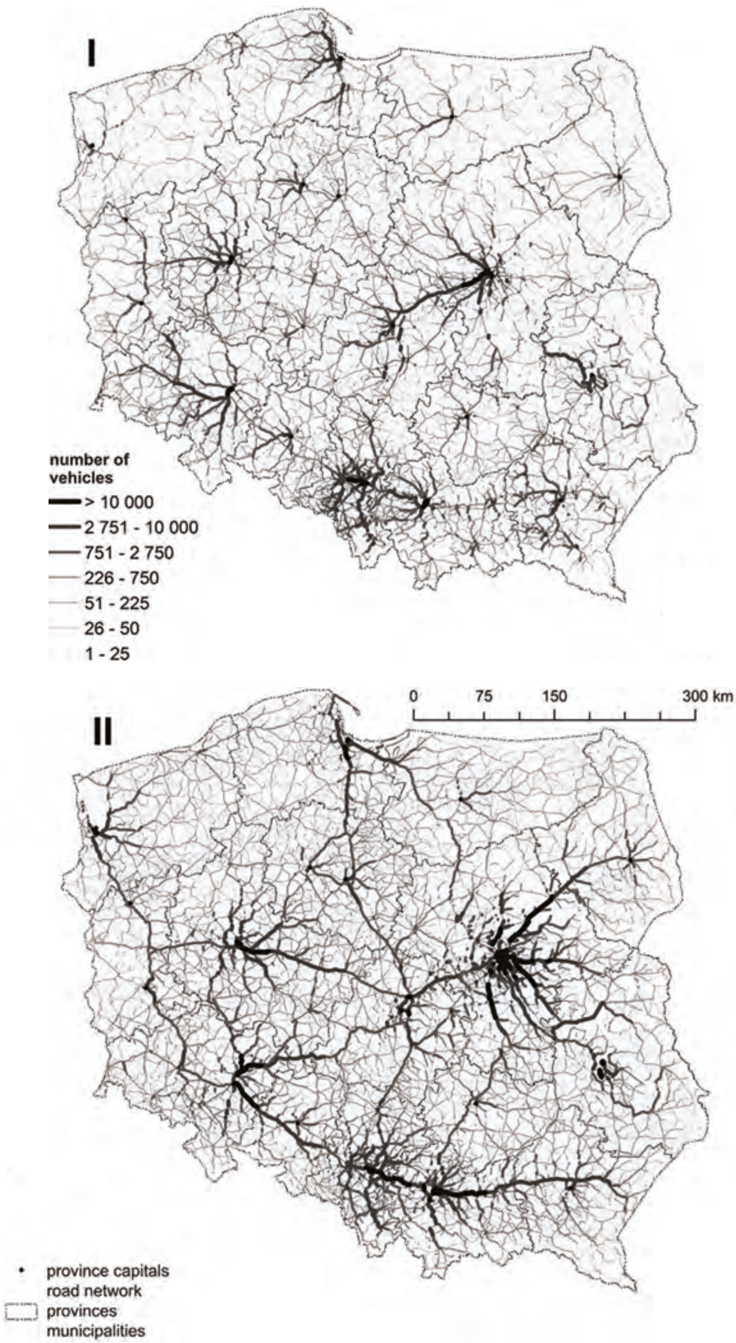


Figure 5.24. Road network load due to commuting (I) and business trips (II) in Poland
Source: own elaboration

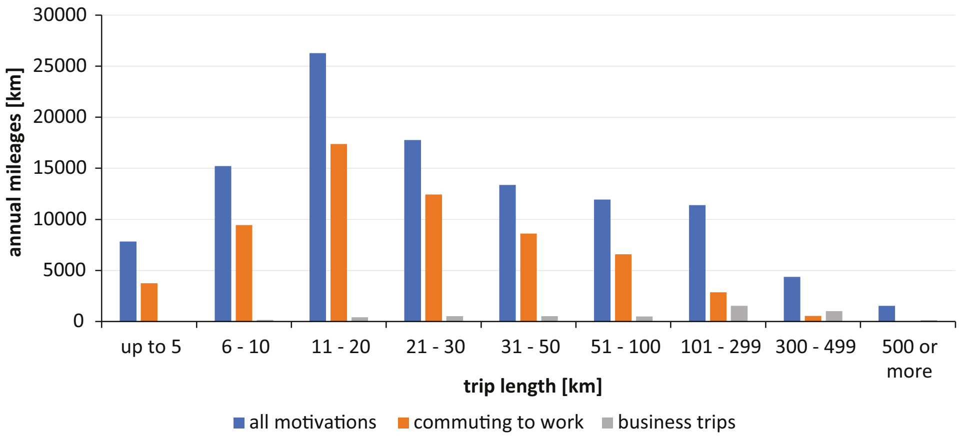


Figure 5.25. Annual passenger car mileages for specified trip lengths for commuting, business trips, and all motivations in Poland in 2015

Source: own elaboration based on data from the Central Statistical Office (2015)

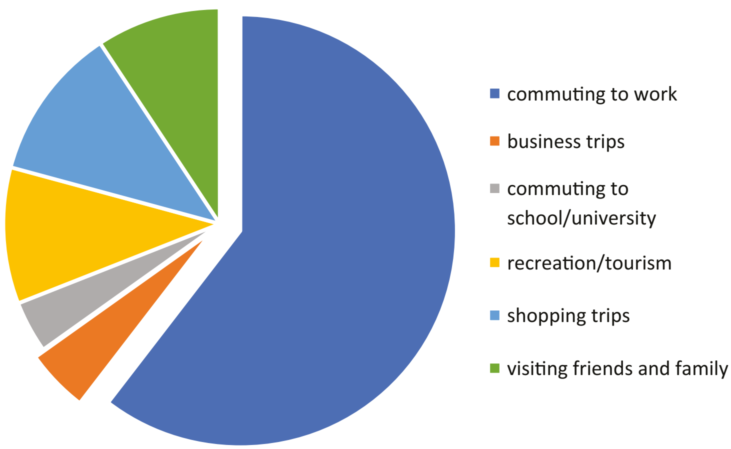


Figure 5.26. The structure of annual passenger car mileages by trip motivation in Poland in 2015

Source: own elaboration based on data from the Central Statistical Office (2015)

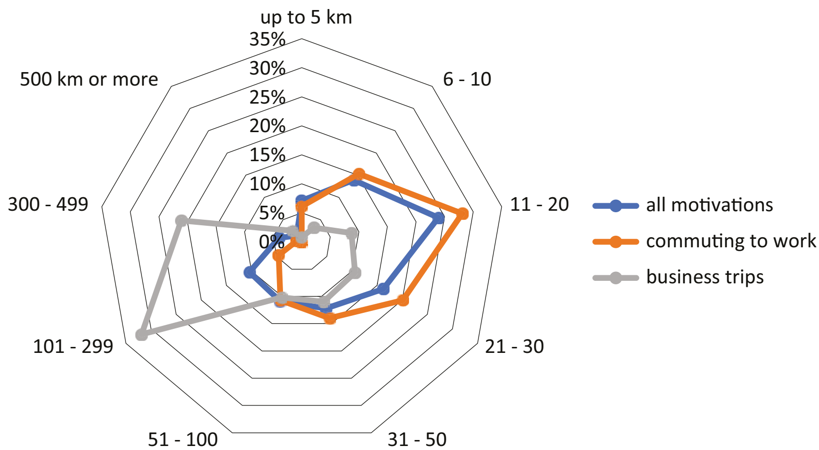
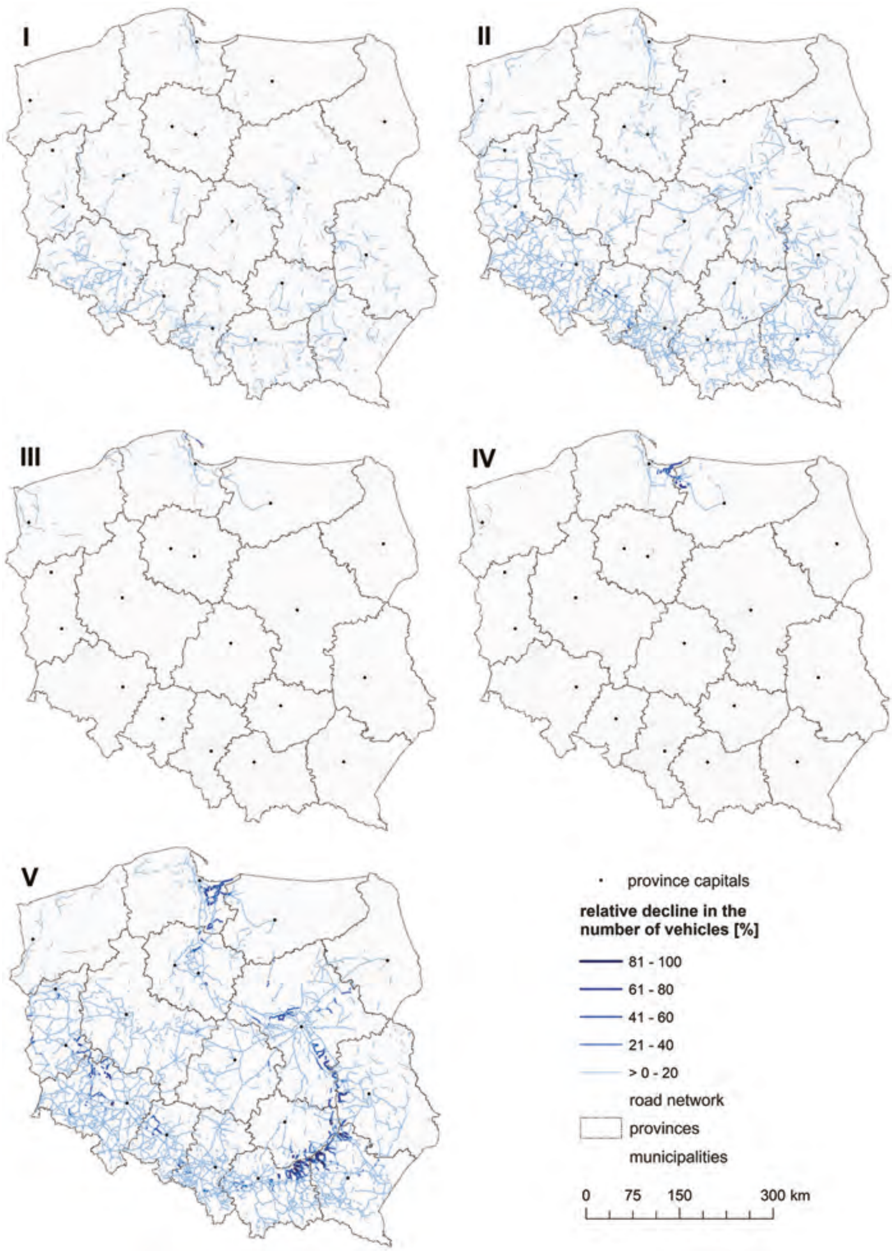


Figure 5.27. The structure of annual passenger car mileages by trip length for commuting, business trips, and all motivations in Poland in 2015
Source: own elaboration based on data from the Central Statistical Office (2015)

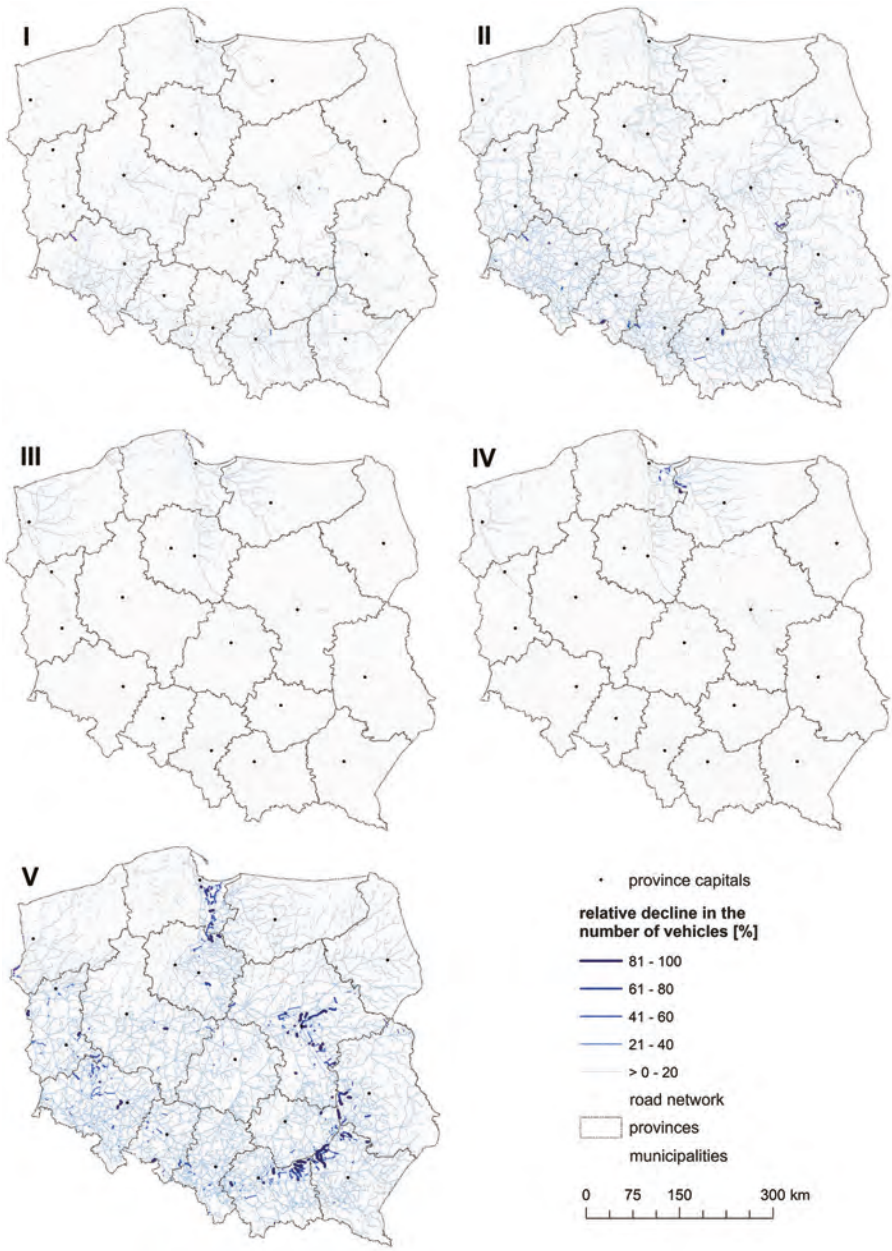
In order to determine the differences in the road network load caused by the different flooding scenarios across different regions in Poland, comparisons were made between the numbers of vehicles on individual segments of the road network in the "normal" scenario and the data generated once traffic was distributed over the network taking into account sections inundated or "cut off" due to flooding of other, adjacent, sections. Similar to the potential accessibility analyses, reductions in the potentials of traffic attraction and production were also applied here during the stage of traffic generation. These potentials were reduced proportionally to the percentage of people living in flood hazard areas in a given scenario against the total population of a given municipality (i.e., if 5% of the population of a given municipality lived within an area where there was a 10% probability of flooding, the traffic production and attraction potentials there were reduced by 5% when simulating how flooding would impact the commuter-related road network load in this scenario). Thus, it was assumed that for the two trip motivations in question, although some trips would be cancelled, others might still emerge due to exceptional circumstances (e.g., flood-related evacuation to places of safety). For commuting, the reduction in traffic generating potentials was implemented without spatial differentiation of flood occurrence and resulted in a decrease in the road network load, as shown in Figure 5.28 (the relative decline in the number of vehicles against the total traffic generated for this motivation). Obviously, the drops that appear are most pronounced for fluvial floods with a 1% probability of occurrence or for flooding due to a breach of stopbanks. When compared with changes of the same type for business trips (Figure 5.29), the smaller spatial scope of the network affected is evident.



I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 5.28. The relative decrease in the number of vehicles within the road network due to the reduction in traffic-generating potentials for commuting to work under different flood scenarios in Poland in 2019

Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 5.29. The relative decrease in the number of vehicles within the road network due to the reduction in traffic-generating potentials for business trips under different flood scenarios in Poland in 2019

Source: own elaboration

5.4. How the RoadLoad application works

For several years, the Institute of Environmental Management and Spatial Policy at the University of Łódź has been working on an application that enables the prediction of changes in the intensity and directions of vehicle traffic flows (traffic distribution over the network). The funds obtained for the project (the results of which are included in this monograph) made it possible to intensify efforts to prepare a prototype version (Borowska et al. 2018, 2020) that initially could operate in an acceptable timeframe on relatively small road network models and in the future would also effectively cover the whole road network in Poland, and to expand it by adding extra features to enhance its operability.

The tool requires two input files (in CSV format), which are, at the same time, a database describing the road network and a matrix resulting from the spatial distribution of trips. As mentioned above, RoadLoad is only applied for the traffic distribution on the road network, the other stages (in line with the four-step model) have to be performed independently by the user.

The first CSV file includes information about the nodes of the network, which are the points depicting places where individual edges (sections) of the network are connected, while others represent centroids of transport regions. Each node is attributed with a unique identification number, which corresponds to the numbering of the nodes in the analogous GIS database and enables interrelations to be created between the two databases. In addition, the attribute description of each node contains information about its geographical coordinates, the number of vehicles that depart from the transport region it represents, and the identification number of the node (transport region) towards which a given volume of vehicles is heading. For instance, if vehicles leave a given node (region) heading to five other nodes (regions), this will be described in the input file with five rows of the table. Additionally, the user has the possibility to specify the delay (by indicating the time value) of departure from particular nodes with respect to the commencement of the whole simulation, and to mark which origin-destination relationship (origin node – destination node) is to be "tracked;" its details specified in the output file of the analysis. "Tracking" a trip allows the exact route(s) of vehicles involved in a given origin-destination relationship to be determined. Any number of relationships may be "tracked."

The second input file contains data on the properties of the network edges (sections). Each of the database rows describes a consecutive edge by assigning its identification number (coinciding with the GIS database), the identification number of the origin and destination node, its maximum capacity, speed in free-flow traffic, and the length of a given network edge. It is possible to introduce any number of other attributes defining individual edges which may influence the choice of travel route (e.g., the monetary cost of covering a given section) when the application is in use. A separate group of edges includes segments that are links between nodes representing connections of network sections and nodes representing trip origins and destinations. These are objects whose properties allow even a large volume of vehicles to reach the node representing the destination transport region without any increase in the travel time resulting from a rise in traffic density on the section.

Once the paths to both files have been specified, the user determines the strategy for designating the weights of individual edges and indicates which attribute(s) from those entered in the input file are to be included in the analysis. In the study presented here, it was travel time only – an attribute that is not entered directly into the database but calculated on the basis of the road section length and the free-flow traffic speed (taking into account the section decay function). In this way, the application deprecates sections that generate higher travel times.

In order to calculate the levels of load for individual elements of the network, the software groups vehicles into abstract objects called "transport packages." Prior to running the application, the user can specify the maximum size (number of vehicles) of these packages. The operation of the application is based on a turn mechanism, where each turn lasts for a precisely stipulated length of time, during which transport packages are "moved" along designated routes within the network. The final input parameter to be entered by the researcher is the duration of individual turns (time intervals). This allows the user not only to view the result of the entire process of traffic distribution over the network, but also to picture it for selected time intervals (30 seconds, 5 minutes, 1 hour, etc.) after the virtual vehicles have appeared on the network.

Once all input parameters have been entered, several auxiliary objects are generated, the most crucial of which are Weight Strategy and Path Calculator. On the basis of the data from the provided CSV files, and in accordance with the designated specifications, the application creates transport packages, establishes their position at the starting nodes, and calculates the shortest (according to the initial guidelines) path to the destination node (these calculations are performed on the unburdened network, which guarantees that the route the package has to travel is the shortest; however, it may still change following subsequent interactions). For this purpose, the Dijkstra algorithm (Dijkstra 1959, Beuthe et al. 2001, Deng et al. 2012, Goyal et al. 2014) and A* algorithm (Fu et al. 2006, Goldberg et al. 2006, Zeng and Church 2009) were implemented. Simulations begin once all the packages have been generated and located within the road network. From the list of all available transport packages, the system selects those which have not reached their destination yet and have already exceeded expected arrival time (since each node can determine the time after which the packages that start there should begin moving, it is possible to conduct a simulation in which new nodes join the network with time). This list is then sorted so that the packages with the shortest route to travel are on top (this prevents packages whose route is congested from being activated in the system before the ones that block them). Another step is to increase the iteration of the internal turn counter of the application. All transport packages in the list from point (B) are set an internal travel time counter in line with the input data entered by the user. This determines how long a given package can be in motion in a given turn. Then, all transport packages are moved (the movement of transport packages is discussed in the following paragraph). The packages that have reached their destinations are transferred onto a separate list and do not participate in further calculations. A file containing a turn report is generated with the data on the load of individual nodes and edges of the network.

The movement of transport packages is divided into two phases. During the first, an attempt is made to move all packages along their routes in line with the following algorithm: (A) a package is moved along the edge of the graph where it is currently located (a node or an edge) by the amount of available time; (B) if, once having been moved, the package has no more time available to move, its status is set to "moved"; (C) if, once having been moved, the package has reached the end of the edge where it is currently located and has not used up all of its movement time, the next point on the package route should be checked; (D) if this next point is blocked (i.e., there are too many vehicles there) or if it does not exist (see below), the package is added to the list of blocked packages and the next package is moved; (E) if the next point on the route is not blocked, the package is moved to its beginning and the procedure restarts at point (A). Once all packages on the list of packages to be moved have been moved, those that have been marked as blocked are selected and phase two begins. During this phase (F) blocked packages are counted; (G) a second list of blocked packages is generated, and within it: (H) their current position is determined; (I) they are moved along the current element they are on; (J) the next points within the route are indicated (if a given package still has movement time available); (K) the package is added to the second list of blocked packages (if no next point exists or exists but is blocked), or if the next point on the route exists and is not blocked, the package is moved to it and the procedure restarts at point (D).

After making an attempt to move all the packages, the researcher must verify whether the first and the second collection of blocked packages have the same sizes. If the second list of blocked items is smaller than the first one (the one with which the algorithm was initiated), it means that one of the packages moved and might have unblocked the movement of the others. In this case, the researcher should proceed to point (A) and then continue with the algorithm. If both lists are the same size, it indicates that the blocked packages have no possibility to move any further. If this is the case, there is the possibility to set a new route to the destination point for each blocked package. Once new routes have been established, the researcher must recurrently activate for them (and only for them) the function of package movement. The application allows traffic to be distributed over a single route, the one that guarantees the lowest total cost of travel (here: time). This solution is suitable for analyses of poorly developed road networks, as it then produces results that are the least different from reality. The computational procedure for this approach is relatively fast and uses the fewest resources. An approach in line with the first principle of Wardrop (the principle of "user equilibrium" flows) is also possible. This is when the network user chooses the path that, from their perspective, offers the lowest cost (here: travel time) and does not choose any other path that fails to guarantee this quality. At this point, the first simplifying assumption occurs, i.e., that each road user has all information on the state of the network. This approach also assumes that all network users perceive costs in the same way (the second simplifying assumption), and that changing the travel path each time results in increased travel costs.

The RoadLoad application generates a set of output files (in CSV format). The first shows the final distribution of traffic over the network. The first column contains the identification numbers of consecutive edges and nodes, the second specifies the total number of vehicles for each component, and the third (and any subsequent column) also contains vehicle numbers that represent the load of subsequent parts of the network, but only those that were within the route taken by vehicles travelling within the "tracked" relationship. Each subsequent "tracked" relationship means another column in the output file. The set of output files also includes summaries containing the aforementioned data, not in the final version, but for each of the predefined turns, thus generating a picture of the road network load in the form of a quasi-stop-motion animation. The application of identification numbers for each network component makes it possible to combine the generated output files with a vector image of the network in GIS software and to represent the size of traffic flows on its individual sections.

6

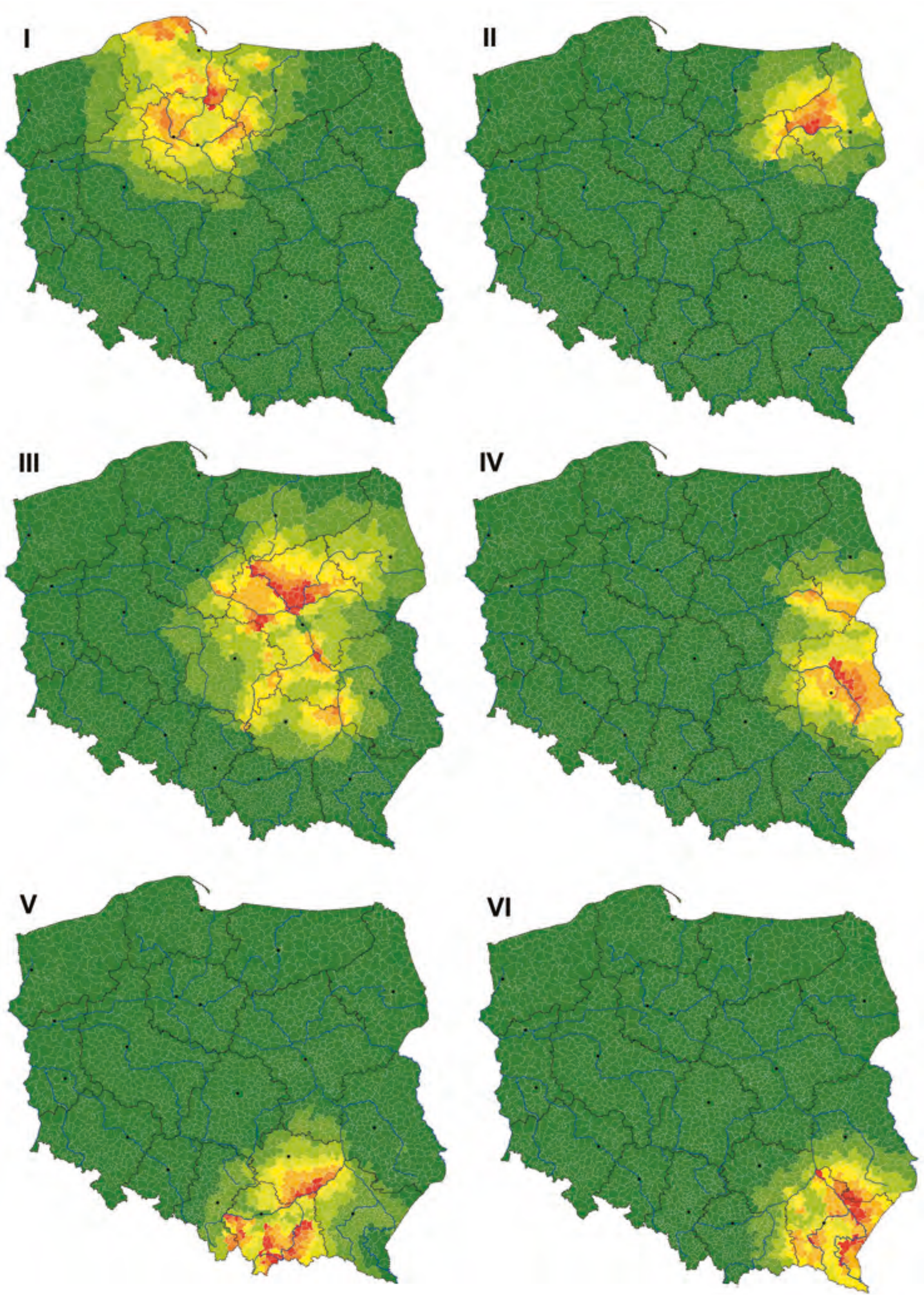
CHANGES IN TRANSPORT ACCESSIBILITY FOLLOWING FLOODS

6.1. Short trips

The results produced when short trips are incorporated into the analyses of flood-related changes in transport accessibility and their spatial differentiation possess a universal set of features and exhibit higher maximum values than for long trips (discussed later in this chapter) with regard to changes in potential accessibility of transport regions. This is due to the important role of the internal potential of transport regions – potential which, as a result of flooding, is degraded across certain areas (affecting population and road network), thereby greatly impacting the final results of the study. The relatively high distance decay makes the accessibility of individual regions dependent on a spatially limited number of adjacent regions and their flood-related weight reductions. As a result, areas affected by decreases in potential accessibility emerge when a flood is simulated in a given water region. In these areas, there are usually a few "islands" suffering peak drops. However, these do not "spread" significantly, and are usually limited to an area similar in size to the water region under simulation. In the vast majority of the analysed flood scenarios and affected areas, the "shadow" of the decline in accessibility for short trips becomes somewhat of a buffer against the areas affected by major decreases. This stems from the fact that the role played by the road infrastructure with the highest parameters (i.e., motorways and expressways) for the distribution of potential accessibility cannot be fully manifested. Another distinctive feature is the clear spatial differentiation obtained for decreases in potential accessibility for individual regions under study.

6.1.1. The Vistula River basin

In all flood scenarios analysed (Figures 6.1–6.3), the largest spatial range of drops in potential accessibility is recorded for the water regions of the Lower Vistula and the Middle Vistula, which primarily results from the number of transport regions affected there.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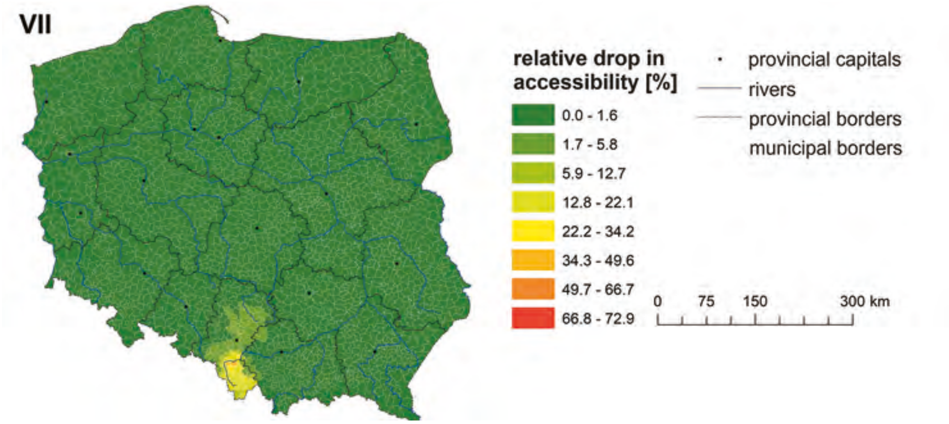
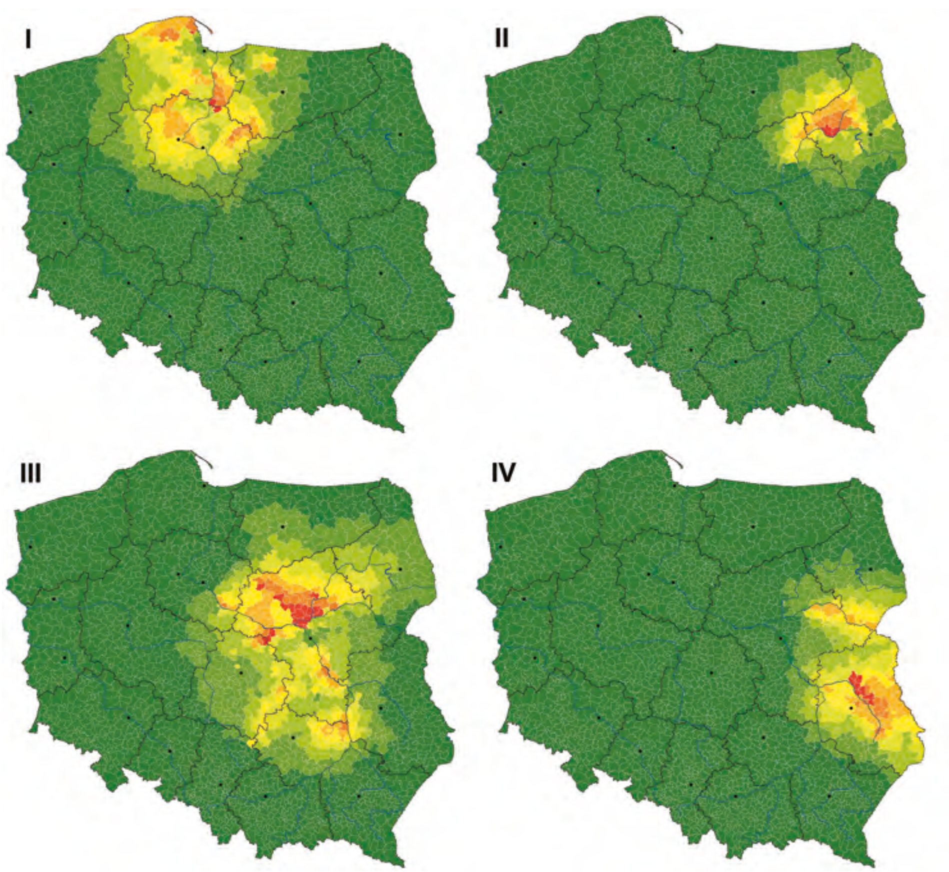
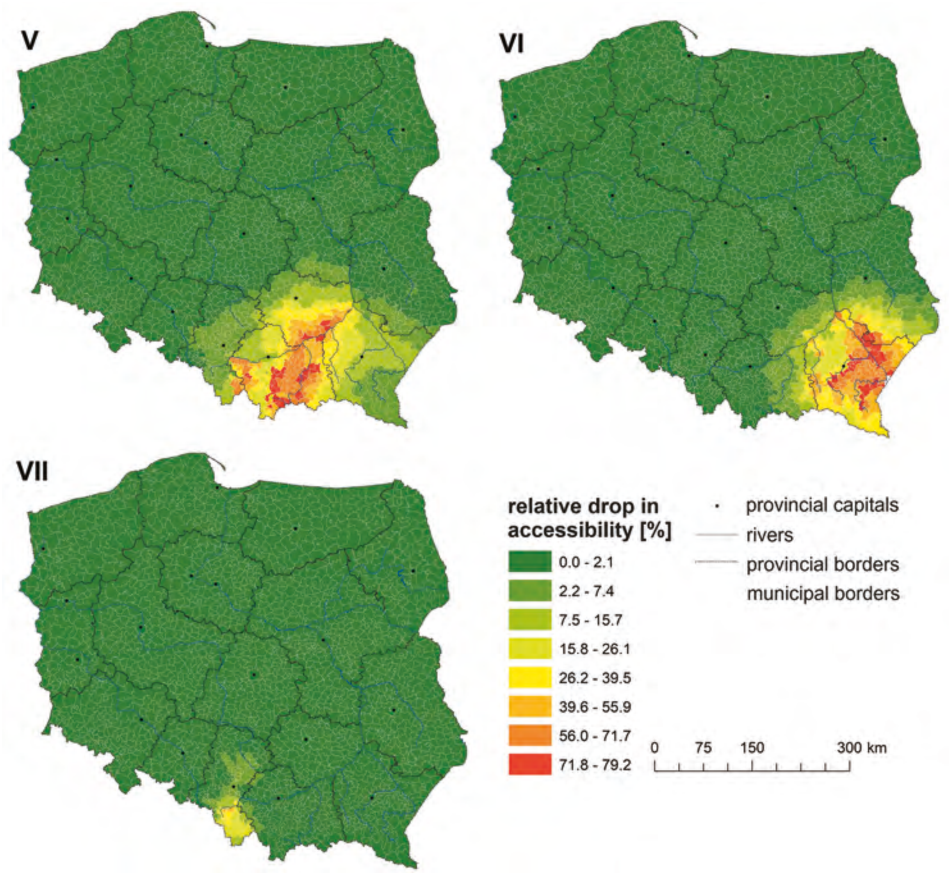


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 6.1. Relative drops in potential transport accessibility for short trips due to a flood with a 10% probability of occurrence in the Vistula basin by water region in Poland in 2019

Source: own elaboration

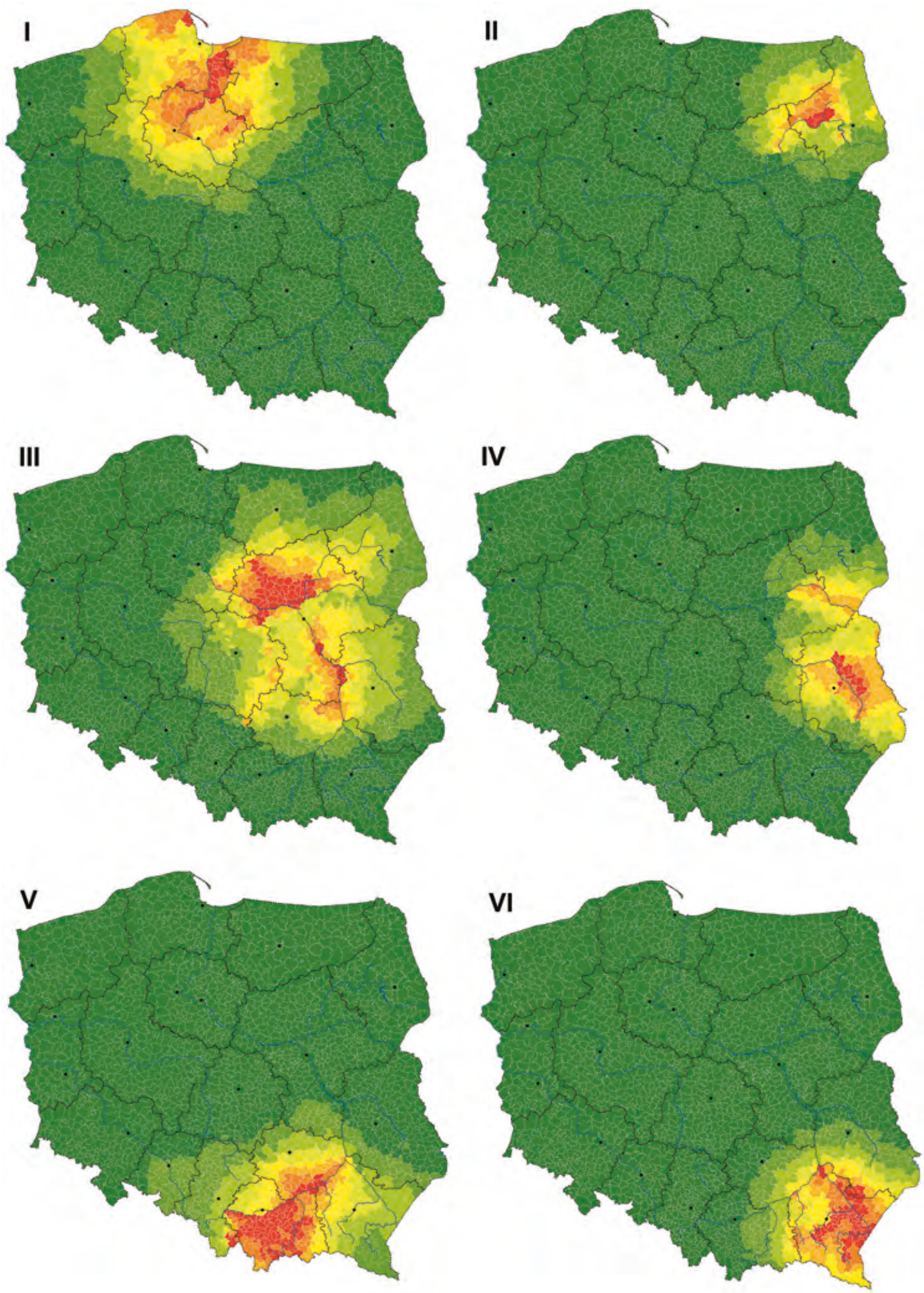




I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 6.2. Relative drops in potential transport accessibility for short trips due to a (fluvial) flood with a 1% probability of occurrence in the Vistula basin by water region in Poland in 2019

Source: own elaboration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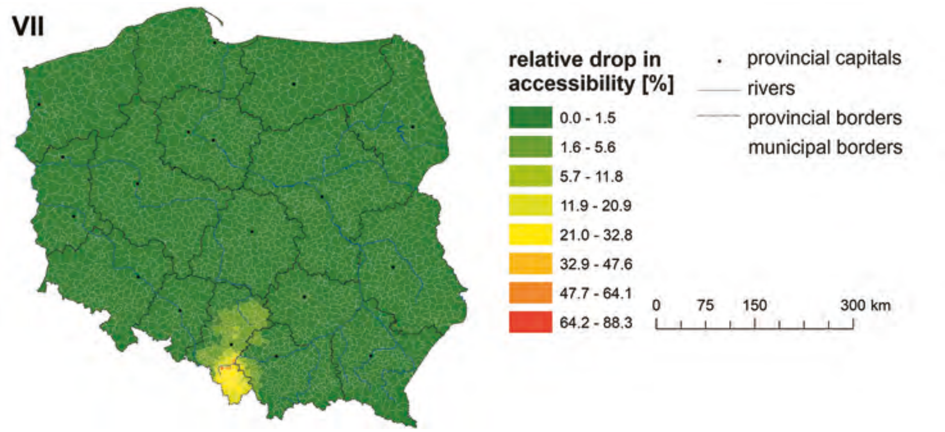


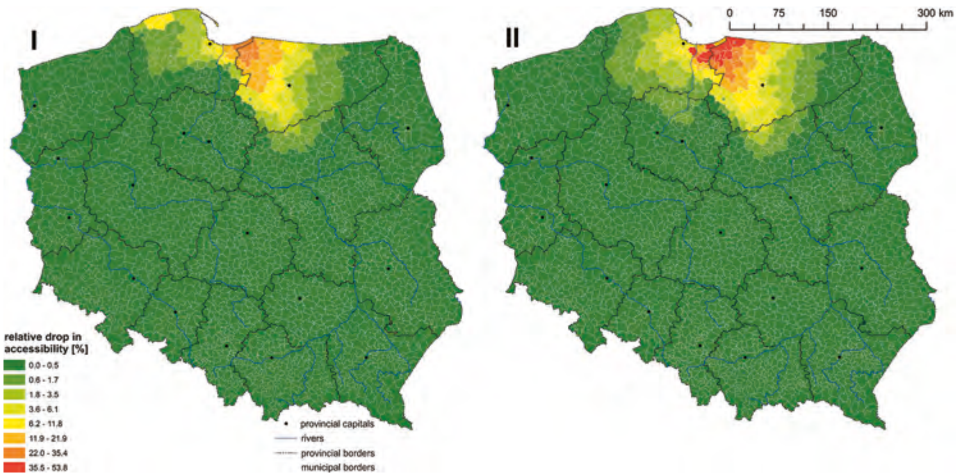
I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug, V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 6.3. Relative drops in potential transport accessibility for short trips following a flood due to a complete breach of stopbanks in the Vistula basin by water region in Poland in 2019

Source: own elaboration

As shown by the analyses of drops in accessibility due to weight reductions of transport regions (see: Chapter 5), it is the scenario with a complete breach of stopbanks in the Middle Vistula and the Lower Vistula that most severely affects this component of accessibility. This scenario also has a particularly negative impact on transport accessibility for transport regions in the district of the Upper Western Vistula. Significant decreases in accessibility are experienced mainly by municipalities in Lesser Poland, which stems, inter alia, from the fact that a high percentage of the population residing there live in areas at risk. Analysis of the cartographic data that present the phenomena discussed above reveals the major impact of motorways and expressways in the spatial distribution of flood-related changes in accessibility.

As indicated earlier in this chapter, the short duration of the trips in question curtails the "spread" of falls in accessibility that these trips cause, sparing transport regions beyond the direct impact of flooding. Although this phenomenon can still be observed, e.g., in the flood scenarios for the Upper Western Vistula (the impact of the A4 motorway) and the Middle Vistula (the impact of the S8 expressway), this type of road infrastructure is so resistant to the damaging effects of floodwaters that it visibly mitigates decreases in accessibility, e.g., the A2 motorway (in all flood scenarios) for the water region of the Middle Vistula, and (again) the A4 motorway – especially for the 10-year flood scenario in the region of the Upper Western Vistula. However, the role of these road classes for moderating flood-related decreases in accessibility depends on their accessibility from the local road network. The magnitude of this protective effect varies depending on both the intensity of flood events and the territorial scope of their impact.



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 6.4. Relative drops in potential transport accessibility for short trips following a flood in a given scenario in the water region of the Lower Vistula in Poland in 2019

Source: own elaboration

A coastal flood (Figure 6.4) is by nature spatially limited and causes fewer adverse effects regarding drops in potential transport accessibility. These can be up to ca. 20 percentage points lower than those observed in fluvial flood scenarios. The situation is most unfavourable in the north-western corner of Warmian-Masurian Province, i.e., the districts of Elbląg, Braniewo, and also (partially) Ostróda and Iława.

In order to determine the impact of floods for the scenarios and regions under study on potential accessibility on a national scale and to conduct a comparative analysis of the severity of this impact in different regions, the values of potential transport accessibility of each transport region under "normal" conditions and under all flood scenarios were aggregated. This made it possible to determine how much accessibility was reduced by flooding against its baseline value, and thus, to calculate the decrease (Figure 6.5). Comparative analyses of the water regions within the basin of the Vistula clearly reveal a worrying picture for the Middle Vistula and the Upper Western Vistula, where a complete breach of stopbanks would be particularly severe for accessibility, when it comes to both the length of the road network excluded from use and the number of people at risk. A purely localised impact on accessibility would be experienced (in all flood scenarios) by the water region of the Little Vistula, which is also confirmed when the resulting falls in accessibility are spatially distributed. Both the number of transport regions where accessibility would decline and the severity of this decrease are small. The picture is slightly different for the water regions of the Bug and the Narew, where for some particular transport regions the impact of disruptions after flooding is noticeably more significant for both the number of settlement units (municipalities) affected and the reduced potential. Interestingly, this is not visible on a national scale, mainly due to the initial potential of the transport regions that would be affected by a flood there. While the reduced potential following a flood would be quite considerable locally for these two regions, its absolute decline is small, especially when compared to the municipalities in the provinces of Łódź, Masovia, Silesia, and Lesser Poland. Thus, when interpreting the results obtained here, one should be aware of the weaknesses of the potential-based method applied in this study, including the risk of underestimating the importance of certain changes in peripheral transport regions (e.g., in the immediate vicinity of state borders).

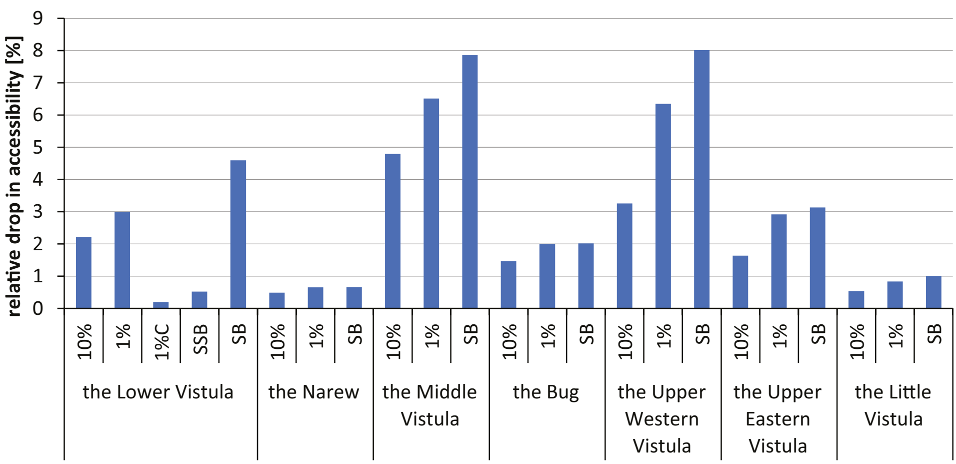


Figure 6.5. Relative drops in potential transport accessibility on a national scale for short trips due to a flood in a given scenario in the Vistula basin by water region in Poland in 2019

Source: own elaboration

Analyses to determine the impact of a flood on transport accessibility are complemented by an examination of changes in the number of affected settlement units (arranged by population size) and the population residing there within the specific lines connecting points of the same travel time (isochrones). Consistent with the methodology outlined in Chapter 5 to analyse short trips, isochrones with values taking multiples of 15 minutes (max. 60 minutes) were generated relative to points for the location of county seats. Table 6.1 below presents the results obtained under the assumption that a flood would breach stopbanks, i.e., the scenario that would bring about the most adverse effects for the transport system.[1] These values show the relative (%) changes in the accumulated components (i.e., settlement units and population) against the "normal" situation for the whole territory of Poland.

Table 6.1. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a complete breach of stopbanks in the Vistula basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Vistula	0–15	settlement units	–1.27	–1.42	–1.48	0.00	–5.26
		population	–1.43	–1.51	–1.76	0.00	–6.13
	15–30	settlement units	–2.09	–1.42	–1.48	–2.13	0.00
		population	–1.48	–1.17	–1.50	–1.85	0.00
	30–45	settlement units	1.81	2.59	0.74	0.00	0.00
		population	1.62	2.45	1.11	0.00	0.00
	45–60	settlement units	0.70	0.00	0.00	0.00	0.00
		population	0.46	0.00	0.00	0.00	0.00
the Narew	0–15	settlement units	–0.16	–0.24	–0.74	–2.13	0.00
		population	–0.11	–0.23	–0.65	–1.84	0.00
	15–30	settlement units	–0.43	0.24	0.74	2.13	0.00
		population	–0.35	0.23	0.65	1.84	0.00
	30–45	settlement units	–0.07	0.00	0.00	0.00	0.00
		population	0.07	0.00	0.00	0.00	0.00
	45–60	settlement units	0.66	0.00	0.00	0.00	0.00
		population	0.39	0.00	0.00	0.00	0.00

[1] Tables presenting the results of all other flood scenarios under study can be found in the Annex.

Table 6.1 (cont.)

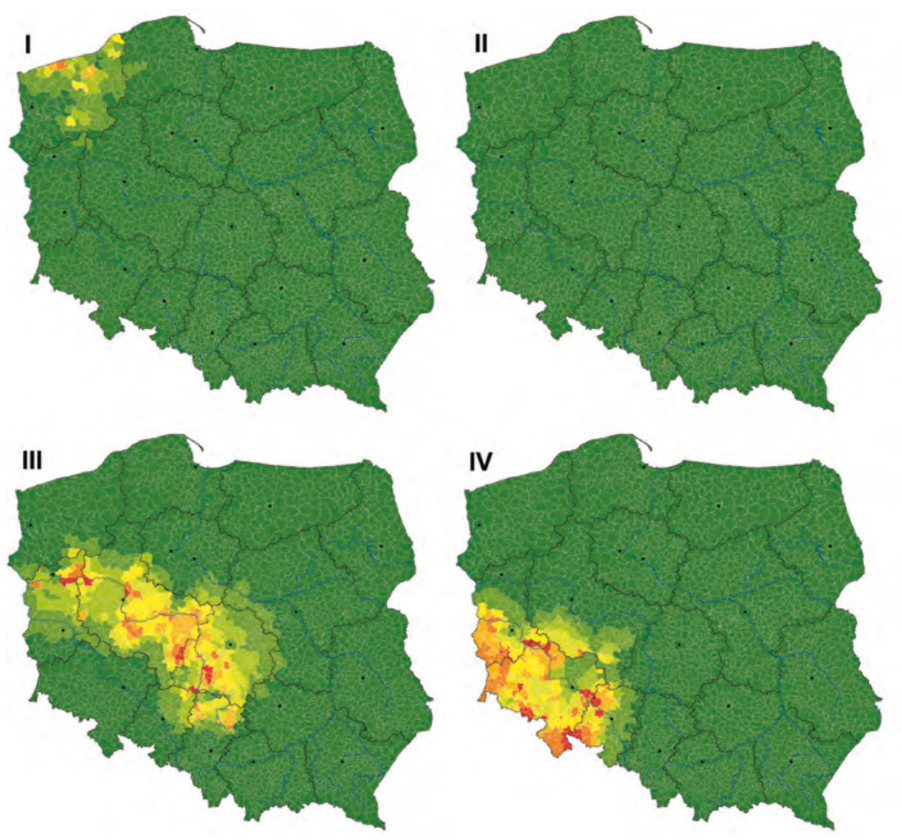
1	2	3	4	5	6	7	8
the Middle Vistula	0–15	settlement units	–0.91	–1.18	–4.44	–4.26	–5.26
		population	–1.17	–1.98	–3.85	–3.67	–16.92
	15–30	settlement units	–2.33	–0.24	2.96	2.13	0.00
		population	–1.31	0.43	2.49	2.03	0.00
	30–45	settlement units	1.60	0.71	0.00	2.13	2.63
		population	1.37	0.75	0.00	1.64	15.83
	45–60	settlement units	0.77	0.00	0.74	0.00	0.00
		population	0.48	0.00	0.70	0.00	0.00
the Bug	0–15	settlement units	–0.28	–0.24	–0.74	0.00	–2.63
		population	–0.37	–0.43	–0.48	0.00	–3.24
	15–30	settlement units	–1.22	–0.71	0.00	0.00	2.63
		population	–1.13	–0.73	0.00	0.00	3.24
	30–45	settlement units	0.45	0.71	0.00	0.00	0.00
		population	0.59	0.73	0.00	0.00	0.00
	45–60	settlement units	0.47	0.00	0.74	0.00	0.00
		population	0.45	0.00	0.48	0.00	0.00
the Upper Western Vistula	0–15	settlement units	–0.30	–0.47	–1.48	–2.13	–2.63
		population	–1.16	–0.35	–1.37	–1.94	–6.95
	15–30	settlement units	–1.26	–0.94	0.00	0.00	0.00
		population	–2.81	–0.64	0.00	0.00	0.00
	30–45	settlement units	0.25	0.47	0.00	2.13	0.00
		population	0.89	0.34	0.00	1.94	0.00
	45–60	settlement units	0.08	–0.24	0.00	0.00	0.00
		population	0.41	–0.29	0.00	0.00	0.00
the Upper Eastern Vistula	0–15	settlement units	–0.33	–0.94	–1.48	0.00	0.00
		population	–1.33	–0.61	–2.04	0.00	0.00
	15–30	settlement units	–0.81	0.00	0.74	0.00	0.00
		population	–1.65	–0.01	0.92	0.00	0.00
	30–45	settlement units	0.24	0.47	0.74	0.00	0.00
		population	1.16	0.35	1.12	0.00	0.00
	45–60	settlement units	0.37	0.47	0.00	0.00	0.00
		population	0.97	0.28	0.00	0.00	0.00
the Little Vistula	0–15	settlement units	–0.03	–0.24	–0.74	0.00	0.00
		population	–0.09	–0.19	–0.83	0.00	0.00
	1–30	settlement units	–0.01	0.00	0.74	0.00	0.00
		population	–0.10	–0.10	0.83	0.00	0.00
	30–45	settlement units	0.04	0.24	0.00	0.00	0.00
		population	0.19	0.29	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

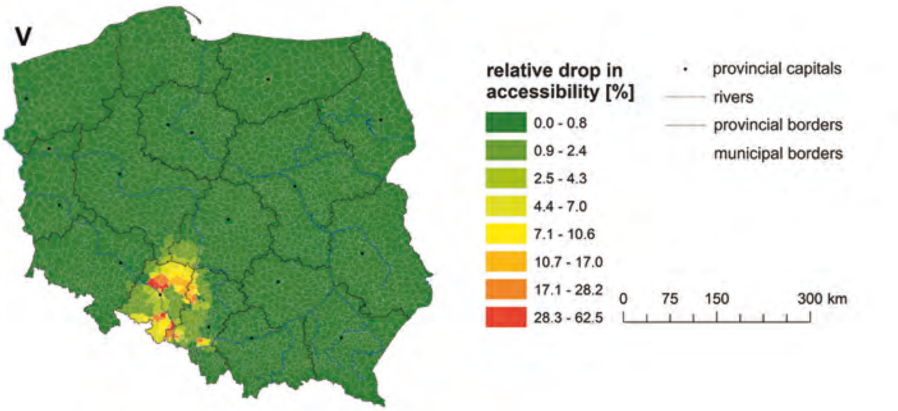
Source: own elaboration.

Among the smallest settlement units (up to 5,000 residents), the impact of flooding on temporal accessibility is visible in all water regions (for the Little Vistula these changes are marginal). Large settlement units experience a decline in temporal accessibility mainly due to flooding in the water regions of the Lower Vistula and the Middle Vistula. Irrespective of the location for which the simulations are conducted, the decrease in temporal accessibility significantly affects those settlement units where the travel time to the county seat is below 15 minutes. This stems from the high density of these units; their even spatial distribution throughout the country, and the high degree of optionality as regards travel routes, which naturally increases along with a rise in travel time that network users opt for. These regularities are also observed for floods with a 10% and a 1% probability of occurrence (fluvial floods), for which the total volume of changes observed is lower by ca. 19% and 8%, respectively.

6.1.2. The Oder River basin

In all flood scenarios (Figures 6.6–6.8) conducted for the Oder basin, the worst adverse effects on transport accessibility (analysed at a local spatial scale) arise from a flood in the water region of the Middle Oder.

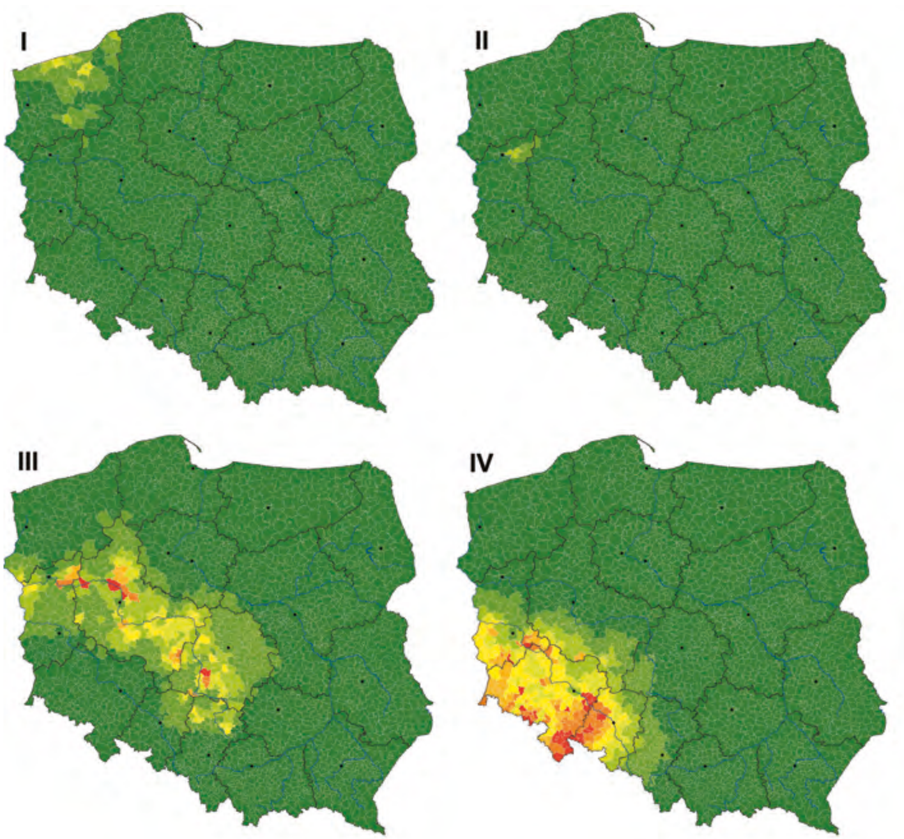


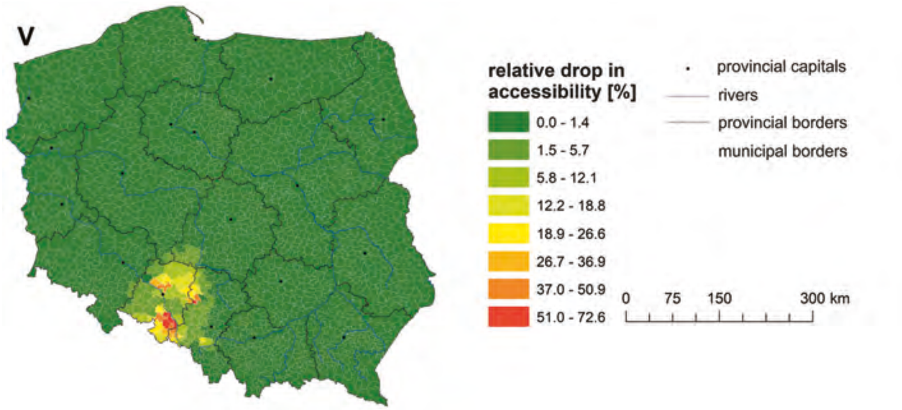


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 6.6. Relative drops in potential transport accessibility for short trips due to a flood with a 10% probability of occurrence in the Oder basin by water region in Poland in 2019

Source: own elaboration

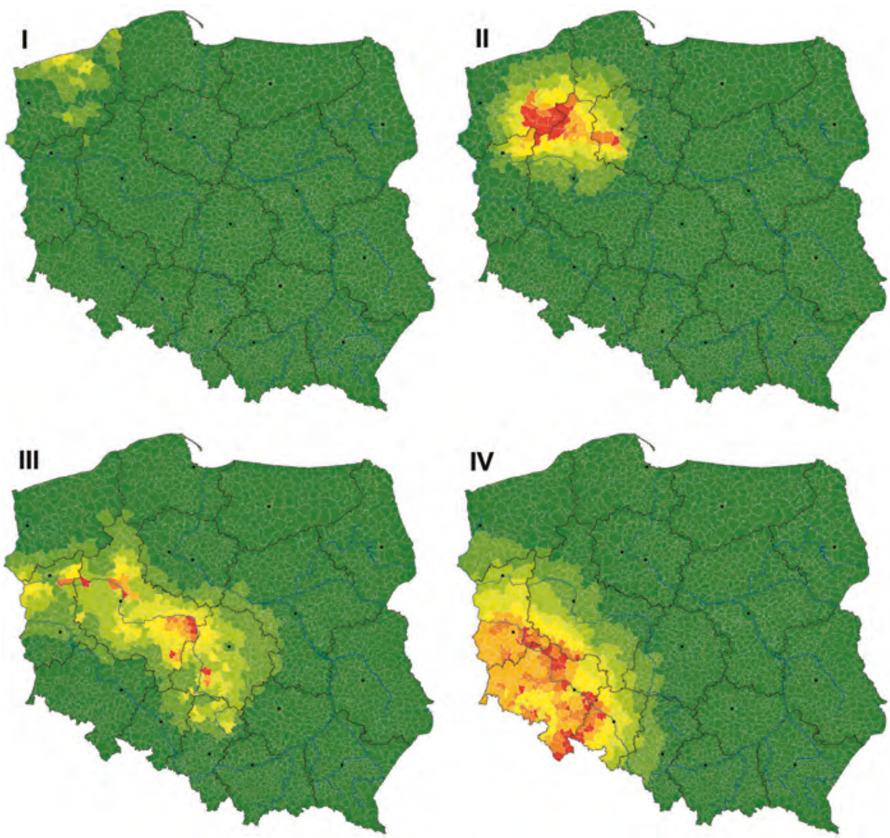


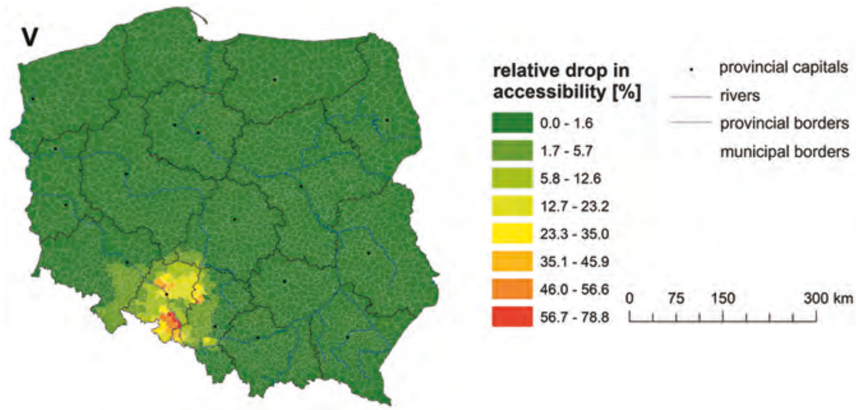


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 6.7. Relative drops in potential transport accessibility for short trips due to a (fluvial) flood with a 1% probability of occurrence in the Oder basin by water region in Poland in 2019

Source: own elaboration



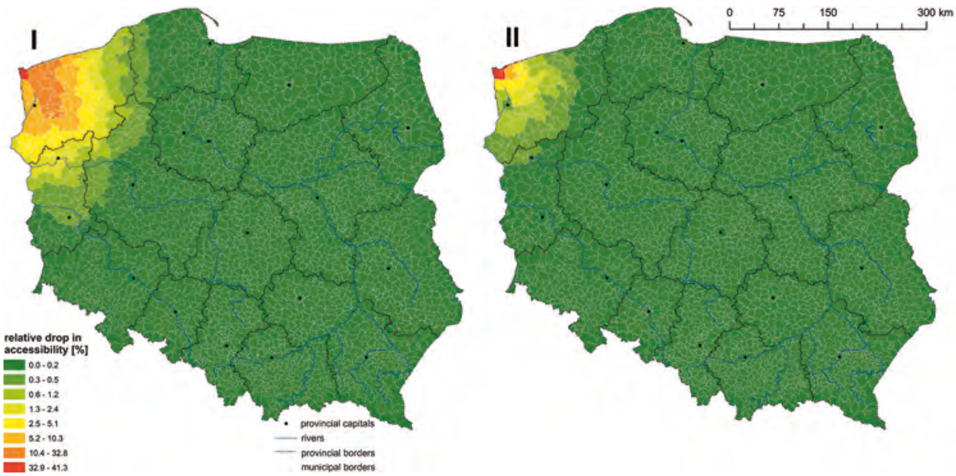


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 6.8. Relative drops in potential transport accessibility for short trips following a flood due to a complete breach of stopbanks in the Oder basin by water region in Poland in 2019

Source: own elaboration

The large spatial scope of the observed reductions is attributable to the size of this water region and the huge number of transport regions where floodwaters directly affect the road network. The highest relative reductions in the potential of transport regions also occur in this water region. For short trips, the initial potential of municipalities in Lubusz Province is not particularly high, so the absolute reductions in accessibility are also small there. However, in Lower Silesia and the western parts of Opole Province there are "islands" that boast a high level of potential accessibility (the city and district of Wrocław, and parts of Brzesko District), where a flood would cause a reduction of over 30%. Analyses of the cartographic data also reveal the possible effects in the water region of the Warta. Given its latitudinal impact of the floodwater, this scenario brings noticeable consequences for transport accessibility across a vast territory. However, significant relative drops in accessibility occur only in certain transport regions, where municipalities do not boast above-average potential even under "normal" conditions. As for the central and eastern parts of Opole Province and the western part of Silesian Province (included in the flood scenario for the water region of the Upper Oder), a major role for the spatial distribution of drops in accessibility is attributed to the A4 motorway, which constitutes a "buffer" against the decreases resulting from disruptions to the road network and changes in the weights of the transport regions, e.g., in the districts of Opole and Kędzierzyn-Koźle.



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 6.9. Relative drops in potential transport accessibility for short trips following a flood in a given scenario in the water region of the Lower Oder and the coastal strip of the West Pomerania in Poland in 2019

Source: own elaboration

Despite the transport regions and the road network of West Pomerania being directly affected by coastal and fluvial floods (Figure 6.9), these would still have no significant impact on the transport equilibrium of the province as a whole. The possible danger due to a fluvial flood in the water region of the Lower Oder and the coastal strip of West Pomerania results in potential drops of up to 10%. It is only the scenario of a complete breach of stopbanks in the water region of the Noteć that may have more far-reaching consequences in the south-eastern parts of the province. As regards coastal floods, they would mostly make potential accessibility drop by only a few percent (except for Świnoujście, where the reduction is more pronounced). During a coastal flood, only sections of the road network located peripherally from the national perspective would be closed off, which means that only the very limited number of trips that would have been made along the affected sections (routes) between the transport regions in question would be affected. As most of these routes are local, drops in potential accessibility would be limited but still noticeable there, while for long trips (analysed later in this chapter) they would only be marginal. The increase in travel time (when it is necessary to find a new, safe route) has a smaller impact on the decrease in potential there, mainly due to a reduction in distance decay.

As regards changes in potential transport accessibility on a national scale (Figure 6.10), the analyses of the flood-related effects in the different scenarios confirm the need to be particularly alert to early signs of the disaster in the water region of the Middle Oder.

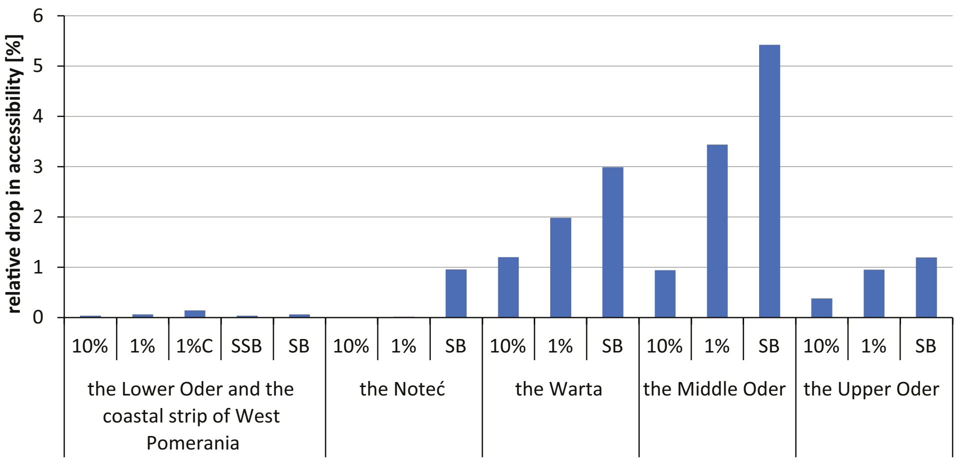


Figure 6.10. Relative drops in potential transport accessibility on a national scale for short trips due to a flood in a given scenario in the Oder basin by water region in Poland in 2019

Source: own elaboration

While a 10-year flood would have very limited consequences for this region, the most dynamic drops in accessibility would be observed in the event a flood with a 1% probability of occurrence or a complete breach of stopbanks. This is why it is critical to continuously monitor the flooding situation there from the very first indications of the likelihood of a flood. The impact of a 10-year flood on the road network would not even cause a 1% decrease in potential accessibility on a national scale and neither would it force network users and operators to significantly change their transport behaviour or traffic organisation. However, timely recognition of the signs that a flood may escalate further than the 10-year threshold will enable the implementation of (technical and organisational) actions that may mitigate its adverse effects, e.g., protecting road infrastructure thereby reducing costs of returning the transport system to its previous norms.

Disruptions to the road network would follow a flood in the water region of the Middle Oder (Table 6.2), resulting in the (locally) most severe deterioration of temporal accessibility. For flood scenarios with a 10% and a 1% probability of occurrence, an increase in travel time would also be observed in the water region of the Warta. However, the relative changes in the number of affected settlement units and residents are noticeably smaller there. Importantly, regardless of the flood scenario, settlement units with populations of between 5,000 and 20,000 are those to which trips would most often be extended in time.

Table 6.2. Relative changes in the number of affected settlement units and the population residing there in the 15-minute intervals of travel time to county seats due to a complete breach of stopbanks in the Oder basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Oder and the coastal strip of West Pomerania	0–15	settlement units	–0.20	0.00	0.00	0.00	0.00
		population	–0.13	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.10	–0.24	0.00	0.00	0.00
		population	–0.09	–0.32	0.00	0.00	0.00
	30–45	settlement units	0.22	0.24	0.00	0.00	0.00
		population	0.13	0.32	0.00	0.00	0.00
	45–60	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.04	0.00	0.00	0.00	0.00
the Noteć	0–15	settlement units	–0.13	–0.24	0.00	0.00	0.00
		population	–0.13	–0.31	0.00	0.00	0.00
	15–30	settlement units	–0.39	–0.24	0.00	0.00	0.00
		population	–0.31	–0.20	0.00	0.00	0.00
	30–45	settlement units	0.34	0.47	0.00	0.00	0.00
		population	0.36	0.51	0.00	0.00	0.00
	45–60	settlement units	0.17	0.00	0.00	0.00	0.00
		population	0.09	0.00	0.00	0.00	0.00
the Warta	0–15	settlement units	–0.39	–0.94	–1.48	0.00	–2.63
		population	–0.39	–1.28	–1.57	0.00	–4.98
	15–30	settlement units	–1.31	–0.71	0.00	0.00	0.00
		population	–0.80	–0.42	0.00	0.00	0.00
	30–45	settlement units	1.17	1.65	1.48	0.00	0.00
		population	0.84	1.70	1.57	0.00	0.00
	45–60	settlement units	0.52	0.00	0.00	0.00	2.63
		population	0.35	0.00	0.00	0.00	4.98
the Middle Oder	0–15	settlement units	–0.73	–1.42	–3.70	–4.26	0.00
		population	–1.07	–1.36	–3.45	–5.64	0.00
	15–30	settlement units	–1.37	–2.36	0.74	0.00	0.00
		population	–1.25	–2.33	0.49	0.00	0.00
	30–45	settlement units	1.30	1.89	0.74	2.13	0.00
		population	1.33	2.06	0.56	3.11	0.00
	45–60	settlement units	0.54	1.42	2.22	2.13	0.00
		population	0.66	1.23	2.40	2.52	0.00

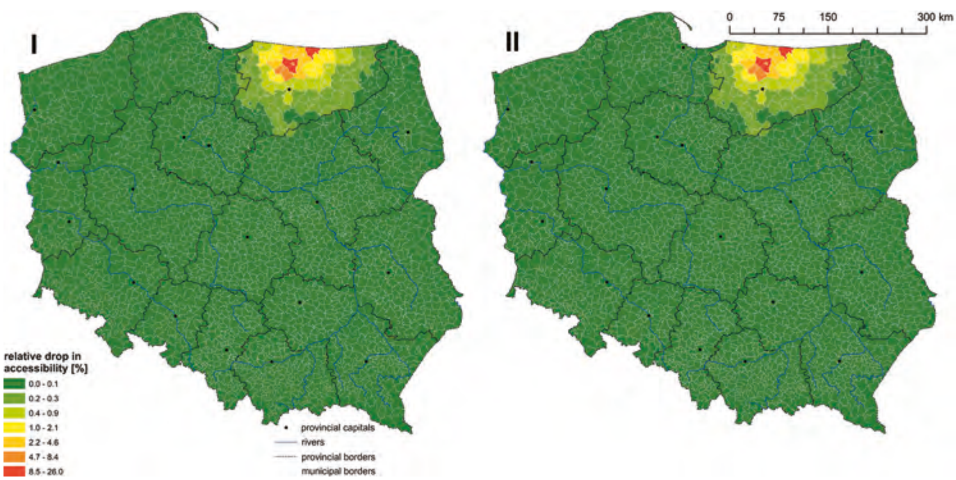
Table 6.2 (cont.)

1	2	3	4	5	6	7	8
the Upper Oder	0–15	settlement units	–0.14	–0.47	–0.74	0.00	0.00
		population	–0.28	–0.51	–0.51	0.00	0.00
	15–30	settlement units	–0.29	0.00	0.00	–2.13	0.00
		population	–0.51	–0.01	–0.36	–1.69	0.00
	30–45	settlement units	0.28	0.24	0.00	0.00	0.00
		population	0.46	0.14	0.00	0.00	0.00
	45–60	settlement units	0.15	0.24	0.74	2.13	0.00
		population	0.34	0.38	0.86	1.69	0.00

Source: own elaboration.

6.1.3. The Pregolya River basin

The impact of a flood on transport accessibility in the smallest river basin analysed herein can only be considered on a local scale, and even then, it is quite limited (Figure 6.11). For any flood probability adopted, the decrease in potential accessibility on a national scale comes close to, but never reaches 0.025%. Drops in the potential observed at the level of transport regions hardly extend beyond the borders of Warmian-Masurian Province, while noticeable consequences for transport accessibility occur only in the districts of Kętrzyn, Bartoszyce, and Olsztyn.



I – 10% probability, II – 1% probability

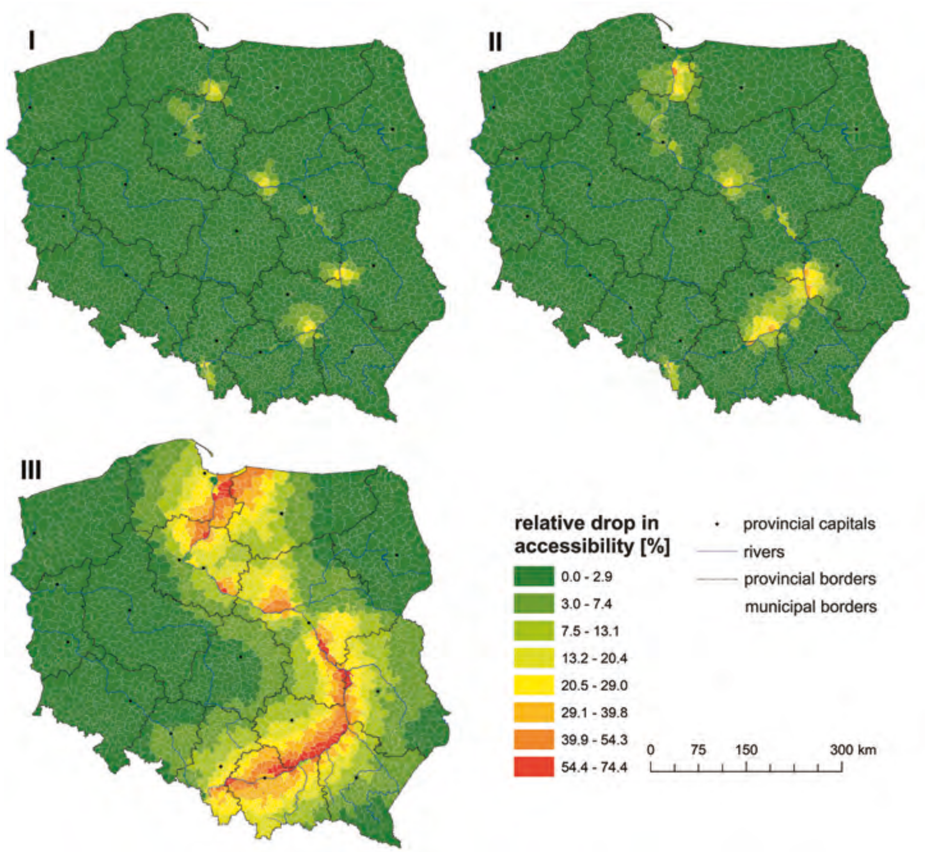
Figure 6.11. Relative drops in potential transport accessibility for short trips following a flood in a given scenario in the water region of the Łyna and the Węgorapa in Poland in 2019

Source: own elaboration

The marginal impact of flooding on the road network in the water region of the Łyna and the Węgorapa is also revealed by analyses of transport accessibility for trips made between individual settlement units. The only increase in travel time is observed for the smallest settlement units (up to 5,000 residents) and affects 0.01% of the population there.

6.1.4. Main rivers

Analyses of changes in transport accessibility for flood scenarios on the main rivers (by length and size of the basin) in Poland (the Vistula, the Oder and the Warta) were not intended to determine how a single flood event along their entire river might simultaneously affect the operation of the road transport. A study of this kind would be burdened with considerable overinterpretation if it did not take into account the temporal changeability of such a spatially extensive flood. The reason further scenarios (for main rivers) were incorporated into the study presented in this monograph was to expand the analyses of changes in transport accessibility for short and long trips with research conducted for a different determination of flood hazard areas than just water regions, i.e., for the entire course of the largest rivers in Poland. As with the analyses based on simulations for individual water regions, the approach for major rivers employed the assumption that all sections of the road network that are flooded or "cut off" within this newly considered area are excluded from operation. This may be perceived as an oversimplification or a weakness of the analysis, which could only be eradicated by further studies that take a more dynamic approach, i.e., analysing the distribution of floodwater flow and road traffic on the network over time. This would, however, require spatial data with a time attribute, both for the flood itself and the road network, since the timing of the return of individual road sections to original operability would still vary, even when the flood has receded. Nevertheless, the approach taken makes it possible to capture patterns that are likely to emerge under the specific conditions of concurrent flooding in quite unlikely spatial configurations (e.g., an extensive flood along the entire course of a given river). Analysis of changes in transport accessibility cannot be conducted under the assumption that flooding occurs simultaneously along the entire length of the river, but rather by employing a set of flood scenarios that make up its entire length, and which are incorporated into the study simultaneously to make the results more intelligible. This approach also allows the researcher to take into account situations where the resilience of the transport network is so low that it is impossible to gradually return individual sections to operation as the floods recede (the simulations for the separate water regions also enable this scenario to be tested). This may result in the emergence of concurrent disruptions to the road network, caused by a series of localised floods that have actually occurred on different sections of the network and at different times.



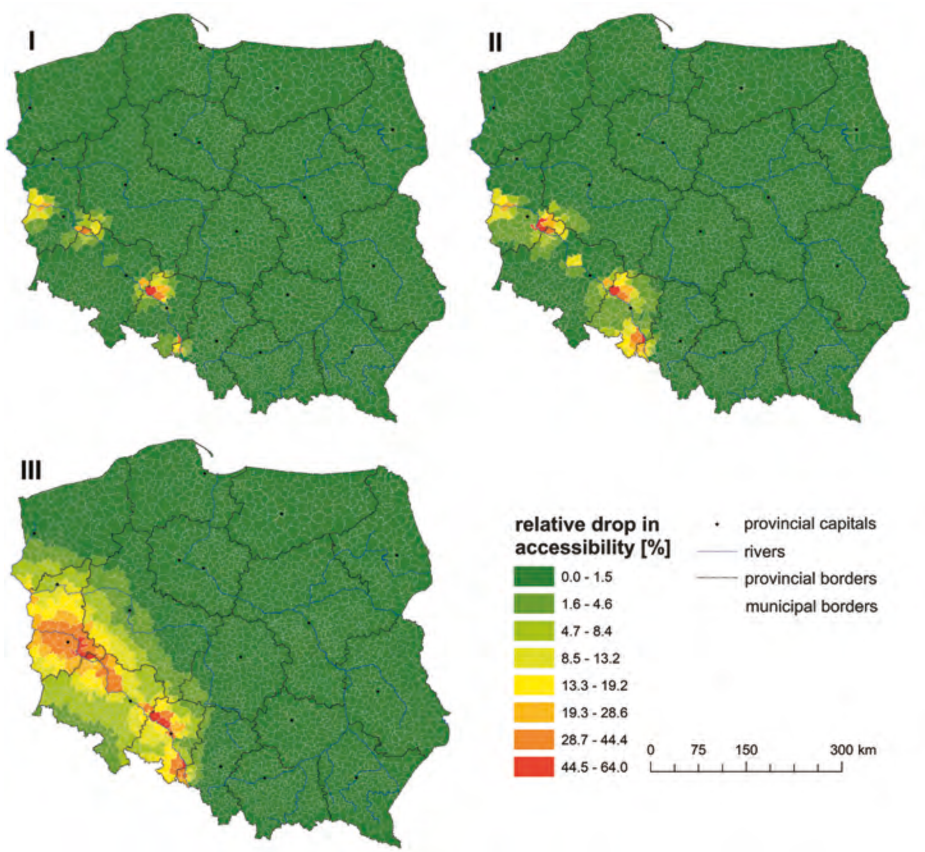
I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 6.12. Relative drops in potential transport accessibility for short trips following a flood on the Vistula in a given scenario in Poland in 2019

Source: own elaboration

For the Vistula (Figure 6.12), a 10-year or even a 100-year flood reduces the potential accessibility of only a small number of transport regions and this reduction is marginal, since road engineering structures are designed to serve their purpose adequately. Even if the threat is extreme, decreases in potential accessibility only occur in isolated areas. These mainly result from closures of road sections important for travelling between adjacent transport regions, which matters significantly when potential accessibility for short trips is to be determined. This particularly affects drops in accessibility in the districts of Kwidzyn, Sztum, Malbork, Płock, and Płońsk. Another factor that aggravates the decrease in accessibility is the reduction of the weights of transport regions, which clearly affects the accessibility in the provinces of Świętokrzyskie, Lesser

Poland, and Subcarpathia. Changes in potential (including internal potential) are significant when analysing short trips and, in combination with the previously mentioned disruption to the local road network, are mainly evident in the districts of Busko-Zdrój, Kazimierza Wielka, Opole, and Kraśnik. A different picture emerges in the scenario of a complete breach of stopbanks. Then, the transport regions affected by a decrease in accessibility form a distinct belt that mirrors the course of the Vistula (although this decrease is significantly reduced in the corridor of the A2 motorway). Comparative analyses of relative drops in potential accessibility on a national scale (Figure 6.15) also clearly indicate that a complete breach of stopbanks on the Vistula is the worst-case scenario, and that it would also have the most adverse consequences when compared to the effects of the same scenario on the other two major rivers.



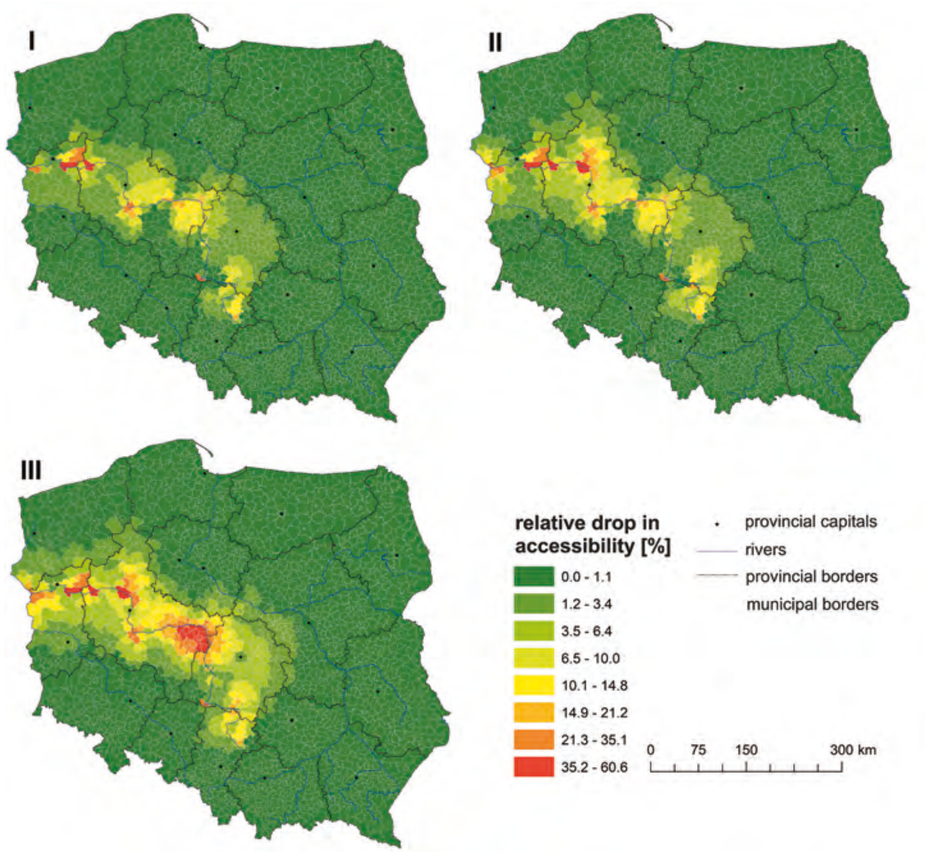
I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 6.13 Relative drops in potential transport accessibility for short trips following a flood on the Oder in a given scenario in Poland in 2019

Source: own elaboration

As regards the scenario with a breach of stopbanks on the Oder (Figure 6.13), this impact would still be considerable, but it would bring significantly smaller spatial decreases in transport accessibility. The robustness of motorways, expressways, and the road engineering structures along their course is manifested in the reduced decline in internal potential of a number of transport regions in the vicinity of the A4 motorway and the S8 motorway.

As regards analyses of flooding on the Warta, a breach of stopbanks and its impact on the accessibility of transport regions in the districts of Międzyrzecz, Oborniki, Śrem, Koniń, and Turek is also worth mentioning. Apart from this worst-case scenario, however, the impact of a flood on the Warta on the potential accessibility at a national scale is similar to the other scenarios in question.



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 6.14. Relative drops in potential transport accessibility for short trips following a flood on the Warta in a given scenario in Poland in 2019

Source: own elaboration

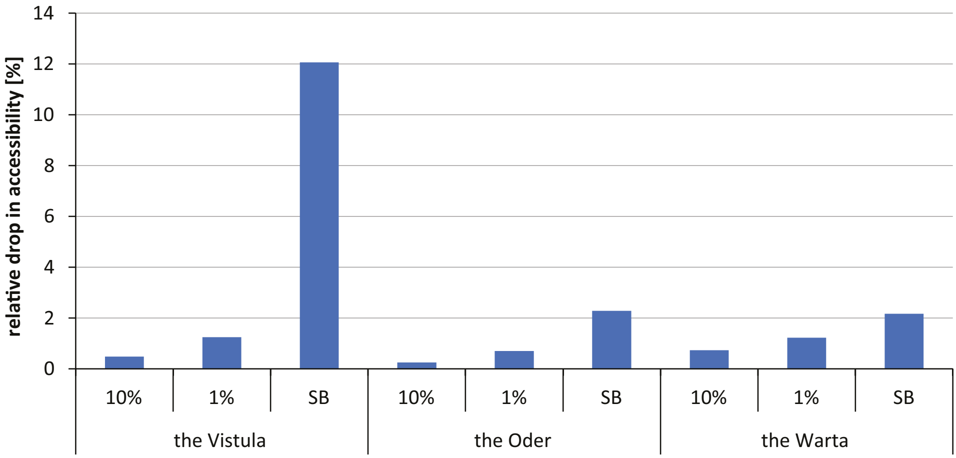


Figure 6.15. Relative drops in potential transport accessibility on a national scale for short trips due to a flood on the main rivers in a given scenario in Poland in 2019

Source: own elaboration

The observed changes in the number of settlement units and the population residing there within 15-minute intervals of the travel time to county seats confirm that neither a 10-year nor a 100-year flood on the Vistula would pose a threat to the territorial cohesion and safety of people (which could also lead to transport exclusion). However, these two flood scenarios reveal a greater susceptibility among sections of the road network that run through the valleys of the Oder and the Warta.

Table 6.3. Relative changes in the number of affected settlement units and the population residing there in the 15-minute intervals of travel time to county seats due to a complete breach of stopbanks following a flood on the main rivers in Poland in 2019 [%]

River	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Vistula	0–15	settlement units	–0.60	–0.94	–2.96	0.00	–10.53
		population	–0.77	–1.25	–2.76	0.00	–25.74
	15–30	settlement units	–1.77	–0.94	0.74	–2.13	5.26
		population	–2.09	–0.41	0.67	–1.85	2.96
	30–45	settlement units	0.62	0.94	0.00	0.00	2.63
		population	0.68	0.85	0.00	0.00	15.83
	45–60	settlement units	1.09	0.71	0.74	0.00	2.63
		population	1.56	0.58	0.58	0.00	6.95

Table 6.3 (cont.)

1	2	3	4	5	6	7	8
the Oder	0–15	settlement units	–0.22	–0.71	0.00	0.00	0.00
		population	–0.39	–0.80	0.00	0.00	0.00
	15–30	settlement units	–0.75	–0.47	–0.74	–2.13	0.00
		population	–0.77	–0.73	–0.86	–1.69	0.00
	30–45	settlement units	0.55	0.71	0.00	0.00	0.00
		population	0.55	0.76	0.00	0.00	0.00
	45–60	settlement units	0.38	0.47	0.74	2.13	0.00
		population	0.58	0.77	0.86	1.69	0.00
the Warta	0–15	settlement units	–0.20	–0.47	–1.48	0.00	–2.63
		population	–0.24	–0.69	–1.57	0.00	–4.98
	15–30	settlement units	–1.02	–0.94	0.00	0.00	2.63
		population	–0.58	–0.74	0.00	0.00	4.98
	30–45	settlement units	1.05	1.42	1.48	0.00	0.00
		population	0.73	1.43	1.57	0.00	0.00
	45–60	settlement units	0.18	0.00	0.00	0.00	0.00
		population	0.09	0.00	0.00	0.00	0.00

Source: own elaboration.

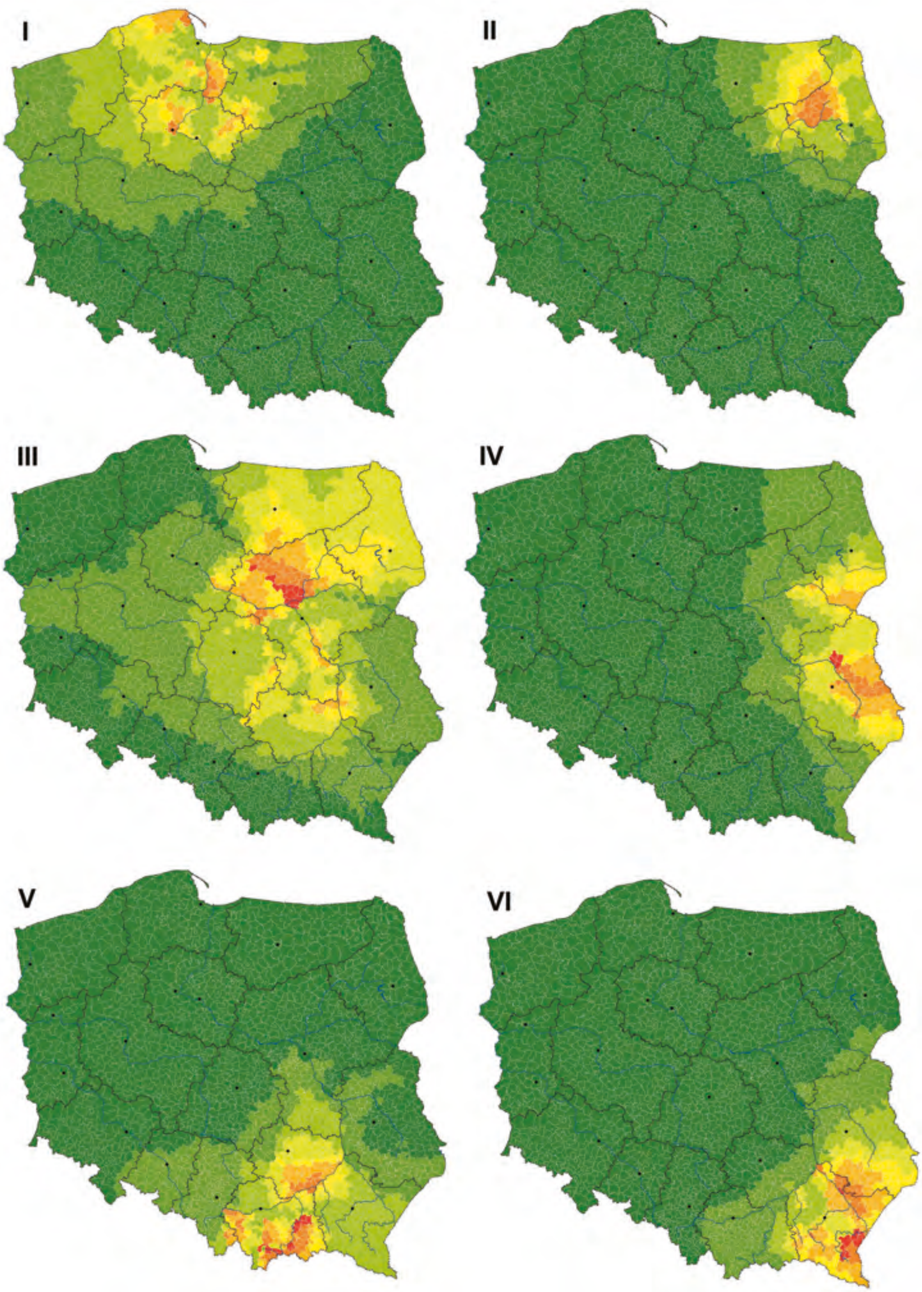
The situation changes drastically for the flood scenario where protection depends on stopbanks (Table 6.3). Then, a noticeably larger portion of the road network is located within areas potentially at risk of flooding on the Vistula. At the same time, the areas in the vicinity of network sections that exhibit low susceptibility to flooding (motorways and expressways) are often deprived of the high level of temporal accessibility that these roads offer due to inundation of roads leading to motorway junctions. For the Oder and the Warta, changes in the delineated isochrones for this scenario do not have a significant impact on the relationships within the settlement network when compared to the changes revealed by the other two analysed scenarios.

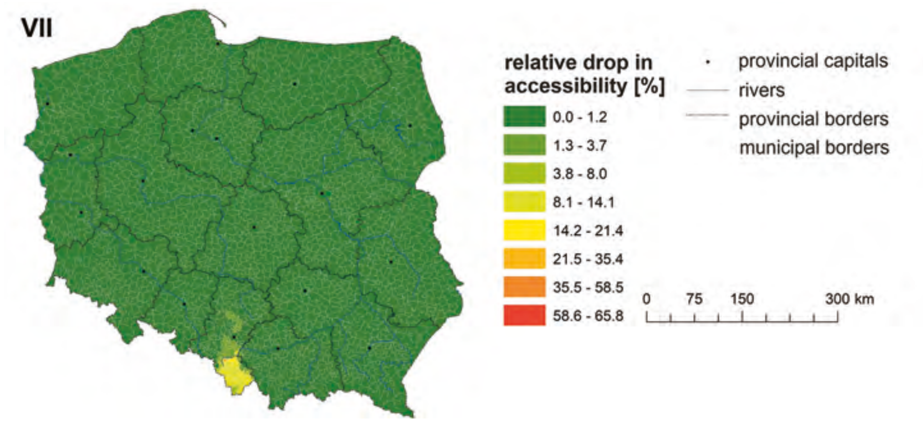
6.2. Long trips

Analyses of flood-related changes in transport accessibility for long trips show a decline in distance decay, which leads to a decrease in how sensitive the dynamics of the reduction in the transport potential of a given transport region is to travel time. Here, the attractiveness of the trip destination drops by half when the travel time is three times longer than was the case for the analysed short trips. For long trips, the reduction in weights of the transport regions affected by flooding and the increase in travel time between them when it would be necessary to avoid the road network sections at risk of flooding results in the following differences when compared to short trips: maximum relative drops in potential accessibility of transport regions are lower (from below 1 to over 20 percentage points, depending on the scenario); the spatial differentiation of the relative drops in potential accessibility of the transport regions under simulation is smaller – the differences in potential between adjacent regions are not so dramatic; in most scenarios under study, the spatial scope of significant changes in transport accessibility is considerably greater; the relative drops in transport accessibility on a national scale are also slightly higher for most scenarios that involve a complete breach of stopbanks (by a maximum of slightly over 3 percentage points); for the remaining flood scenarios, the drops are generally lower, albeit the differences are considerably smaller and do not exceed 0.75 percentage point. These differences can also be explained by the greater number of transport regions whose weights make up potential accessibility of individual municipalities. In most cases, this requires the weights of regions outside the direct impact of flooding (no reduction in attractiveness) to be included, which – given the relatively low distance decay – are also slightly reduced. This means that, when determining the relative drops in potential accessibility, the weight reduction of the region affected by flooding (the accessibility of which is assessed) and the reductions experienced by the regions included in the same scenario are compared to larger values than those for short trips. In exceptional cases, when the disruption to the road network and the percentage of the population living in areas at risk of flooding are very extensive and affect a large number of transport regions, e.g., when there are no stopbanks to provide protection against flooding, this regularity would naturally aggravate the drops in accessibility when compared to those observed for short trips.

6.2.1. The Vistula River basin

Disruptions to the cohesion of the road network and the attractiveness of transport regions for long trips during a flood in the different water regions of the Vistula bring adverse effects for the transport accessibility of municipalities in all provinces of Poland. An exception to this is the water region of the Little Vistula (Figures 6.16–6.18), where drops in potential accessibility concentrate in Silesian Province and are marginal in other regions (little increase is also seen when a flood is simulated that affects large areas). In all other cases, the consequences are supra-regional. As regards spatial scope, the occurrence of a flood in the water region of the Middle Vistula has the greatest negative impact on the transport system. In all scenarios, the flood-related drops in potential accessibility reach values of a few percent for all 16 provinces. However, the results of the analyses that consider changes in potential accessibility on a national scale indicate that this scenario is most problematic only if there is a flood with a 10% probability of occurrence (Figure 6.20). As for a 100-year flood, it is most disruptive to the road transport system (as regards accessibility) when it occurs in the water region of the Upper Western Vistula. A complete breach of stopbanks in this area would also cause far greater disturbances of potential accessibility than in the other flood scenarios.

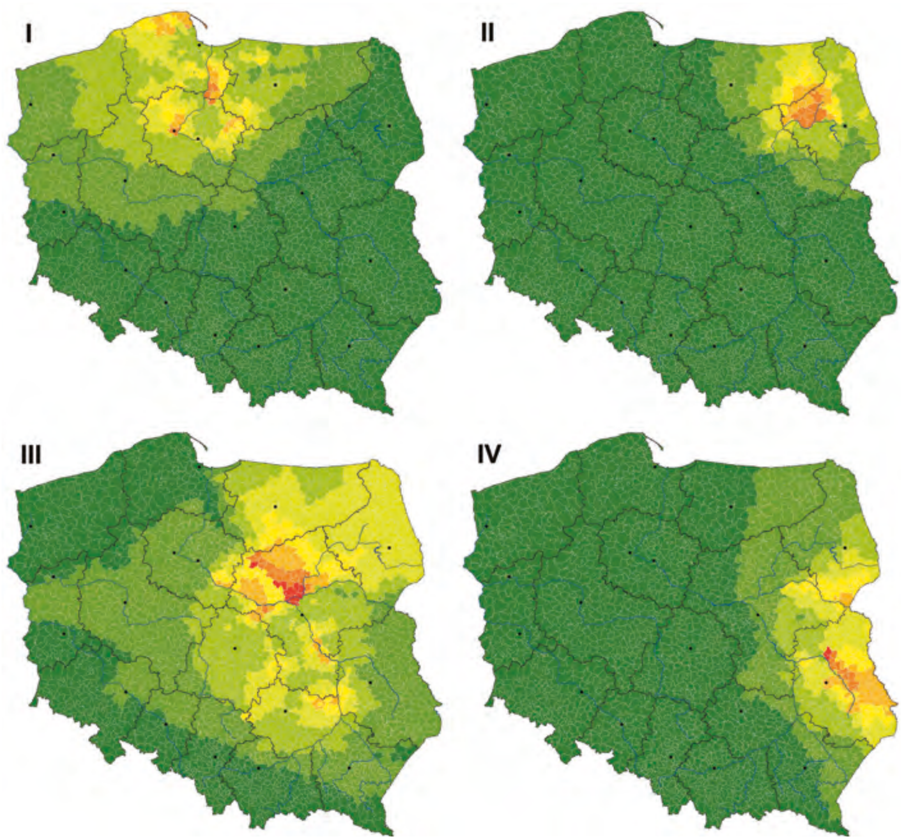


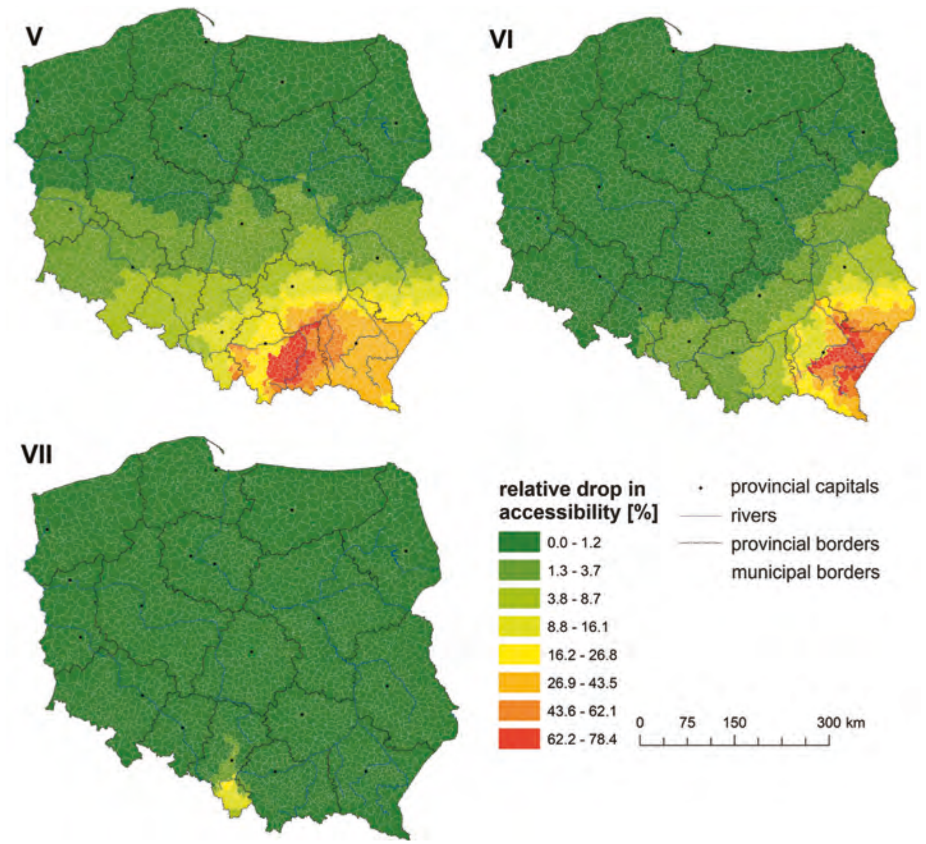


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 6.16. Relative drops in potential transport accessibility for long trips following a flood with a 10% probability of occurrence in the Vistula basin by water region in Poland in 2019

Source: own elaboration

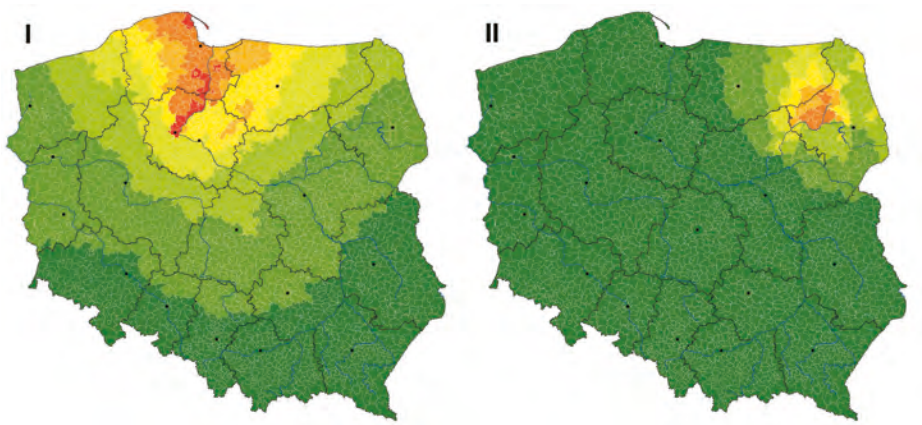


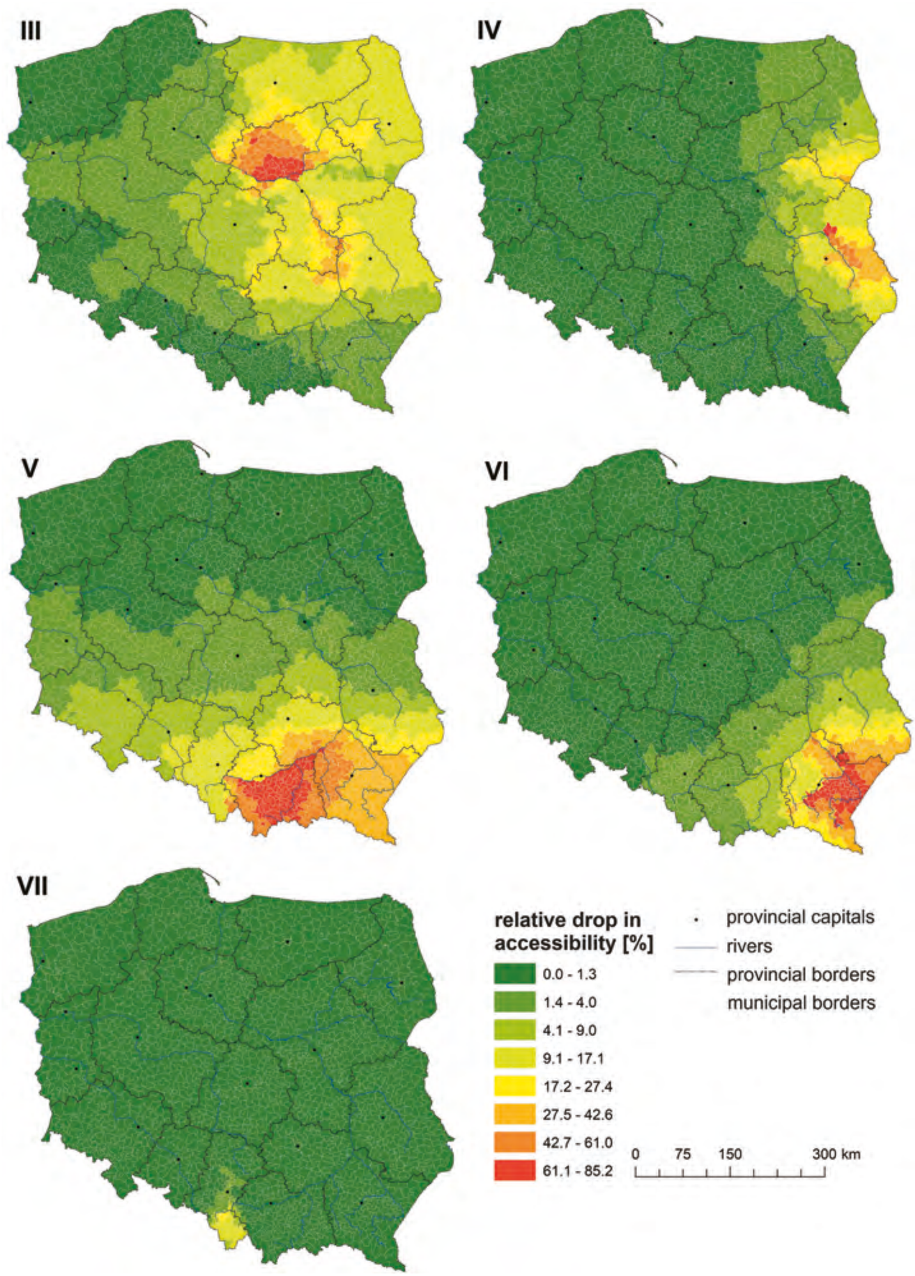


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 6.17. Relative drops in potential transport accessibility for long trips following a (fluvial) flood with a 1% probability of occurrence in the Vistula basin by water region in Poland in 2019

Source: own elaboration



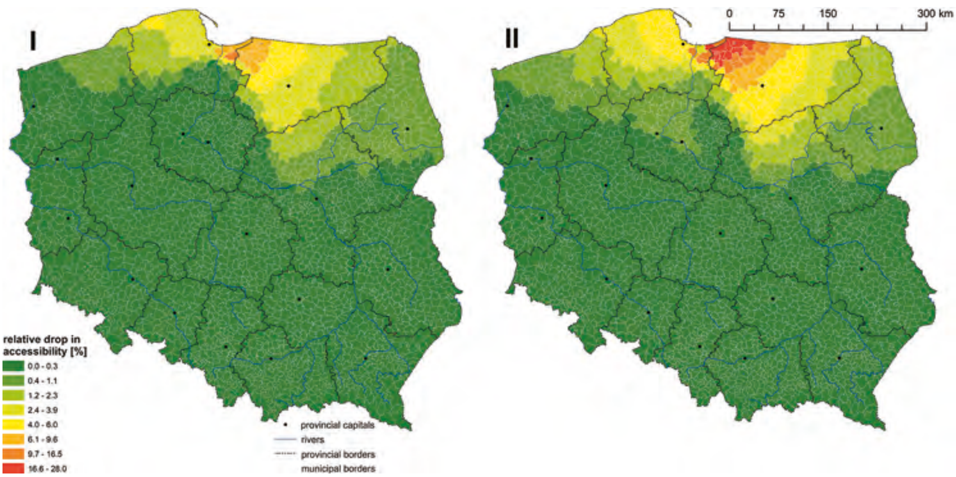


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 6.18. Relative drops in potential transport accessibility for long trips following a flood due to a complete breach of stopbanks in the Vistula basin by water region in Poland in 2019

Source: own elaboration

As regards long trips, section closures on the road network due to a coastal flood within the Vistula basin would have a very limited impact on potential accessibility (Figure 6.19). Despite the large percentage of people residing in areas at risk of flooding within the total population of the transport regions affected by floodwaters (especially in the scenario with a complete breach of the protective structure of the service strip), the presence of the highly resilient road infrastructure (e.g., the S7 expressway and the road engineering structures along its course) prevents a dramatic increase in travel times to other destinations and does not exacerbate drops in potential accessibility.



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 6.19. Relative drops in potential transport accessibility for long trips following a flood in a given scenario in the water region of the Lower Vistula in Poland in 2019

Source: own elaboration

These minor fluctuations in accessibility are also confirmed by a breakdown of its relative drops on a national scale (Figure 6.20). Their level is similar to the decrease observed following a flood in the water region of the Little Vistula and does not exceed 0.5%.

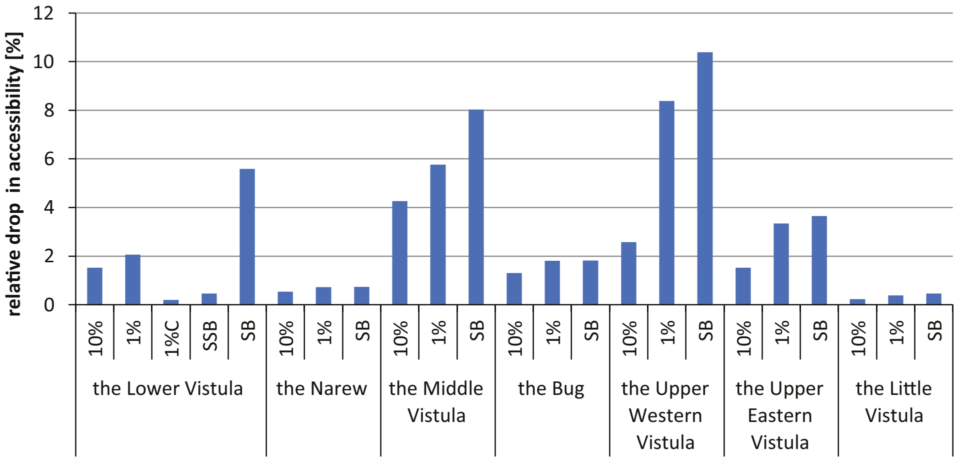


Figure 6.20. Relative drops in potential transport accessibility on a national scale for long trips due to a flood in a given scenario in the Vistula basin by water region in Poland in 2019

Source: own elaboration

Similarly to short trips, the impact of flooding on accessibility was also measured by the relative change in the number of settlement units and their population against specified destinations within defined travel time zones. For long trips, however, the destinations were provincial capitals and the time intervals adopted equalled 30 minutes (Table 6.4).

Table 6.4. Relative changes in the number of affected settlement units and the population residing there in the 30-minute intervals of travel time to provincial capitals due to a complete breach of stopbanks in the Vistula basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Vistula	0–30	settlement units	–0.70	–1.18	–0.74	0.00	–5.26
		population	–0.95	–1.12	–0.65	0.00	–6.13
	30–60	settlement units	–2.77	–2.83	–3.70	–2.13	–2.63
		population	–2.24	–2.93	–3.48	–1.85	–1.17
	60–90	settlement units	–0.69	–0.47	–0.74	–2.13	2.63
		population	–0.17	–0.76	–1.34	–2.33	1.17
	90–120	settlement units	2.20	2.83	2.22	0.00	0.00
		population	1.74	3.02	2.42	–0.57	0.00

Table 6.4 (cont.)

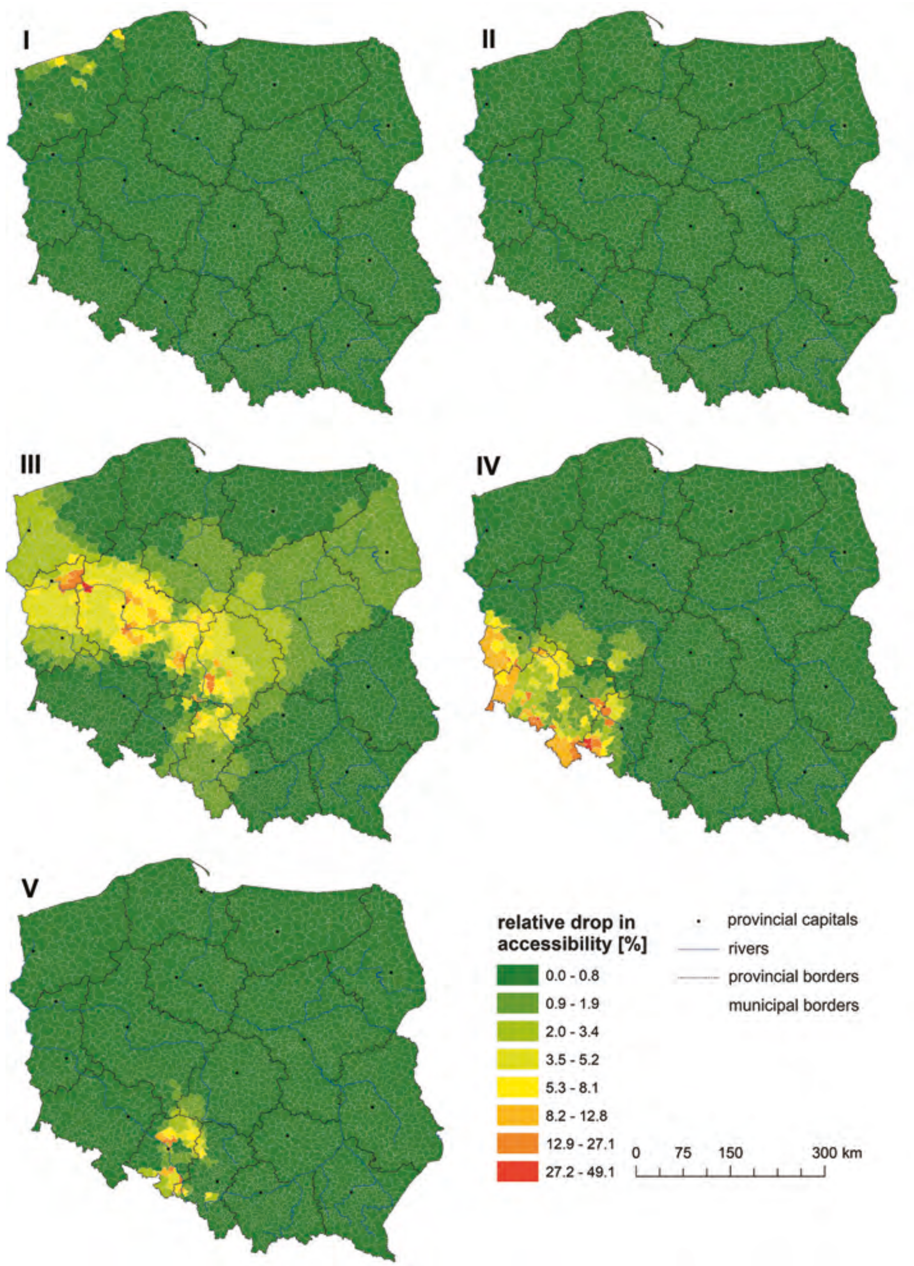
1	2	3	4	5	6	7	8
the Narew	0–30	settlement units	–0.05	–0.47	0.00	0.00	0.00
		population	–0.05	–0.60	0.00	0.00	0.00
	30–60	settlement units	–0.16	0.47	0.00	–2.13	0.00
		population	–0.06	0.60	0.00	–1.93	0.00
	60–90	settlement units	–1.05	–0.24	–0.74	2.13	0.00
		population	–0.60	–0.24	–0.52	1.93	0.00
	90–120	settlement units	0.03	0.24	0.00	0.00	0.00
		population	0.03	0.24	0.00	0.00	0.00
the Middle Vistula	0–30	settlement units	–0.45	–2.59	–4.44	–2.13	–2.63
		population	–0.95	–3.29	–4.20	–1.81	–15.83
	30–60	settlement units	–4.00	–3.30	–5.93	–2.13	–2.63
		population	–3.68	–3.76	–6.05	–1.65	–1.09
	60–90	settlement units	–3.86	0.94	5.19	–2.13	–2.63
		population	–1.67	1.18	4.68	–2.84	–1.19
	90–120	settlement units	4.98	3.77	3.70	4.26	5.26
		population	4.15	4.71	4.38	4.65	17.02
the Bug	0–30	settlement units	–0.45	–0.24	–2.22	0.00	–2.63
		population	–0.78	–0.16	–1.96	0.00	–3.24
	30–60	settlement units	–1.65	–0.47	0.00	–2.13	0.00
		population	–1.42	–0.82	–0.22	–2.06	0.00
	60–90	settlement units	–1.67	–1.18	0.74	–2.13	2.63
		population	–1.28	–1.80	0.97	–2.06	3.24
	90–120	settlement units	0.48	0.47	0.74	0.00	0.00
		population	0.62	1.02	0.73	0.25	0.00
the Upper Western Vistula	0–30	settlement units	–0.53	–1.42	–1.48	0.00	–2.63
		population	–1.58	–1.42	–1.05	0.00	–6.95
	30–60	settlement units	–1.73	–2.83	–1.48	0.00	0.00
		population	–3.49	–2.65	–1.64	0.00	0.00
	60–90	settlement units	–0.42	–1.42	–1.48	–2.13	0.00
		population	–1.76	–0.62	–1.20	–2.64	0.00
	90–120	settlement units	0.18	–0.47	0.00	0.00	0.00
		population	–0.68	–0.26	0.11	0.00	0.00
the Upper Eastern Vistula	0–30	settlement units	–0.11	–0.47	0.00	0.00	0.00
		population	–0.59	–0.56	0.00	0.00	0.00
	30–60	settlement units	–0.65	–2.36	–1.48	0.00	0.00
		population	–2.15	–2.07	–2.04	0.00	0.00
	60–90	settlement units	–1.10	0.71	–2.22	–2.13	0.00
		population	–2.21	0.71	–2.94	–2.01	0.00
	90–120	settlement units	–0.01	0.00	1.48	0.00	0.00
		population	0.47	0.00	2.02	0.00	0.00
the Little Vistula	0–30	settlement units	–0.02	–0.47	0.00	0.00	0.00
		population	–0.03	–0.34	0.00	0.00	0.00
	30–60	settlement units	–0.12	–1.42	–0.74	0.00	–2.63
		population	–0.63	–1.39	–0.83	0.00	–1.65
	60–90	settlement units	0.04	0.71	0.00	0.00	2.63
		population	0.17	0.92	0.07	0.00	1.65
	90–120	settlement units	0.09	1.18	0.74	0.00	0.00
		population	0.46	0.81	0.76	0.00	0.00

Source: own elaboration.

For the scenarios with a 10% and a 1% probability of flooding in the Vistula basin, the temporal accessibility to provincial capitals would drop significantly due to a flood in the water regions of the Lower Vistula and the Bug. In the event of a 100-year flood, a considerable change in the shape of the isochrones of travel time to provincial capitals is also observed for the water regions of the Middle Vistula and the Upper Eastern Vistula. In both cases, the increase in travel time is particularly pronounced for transport relationships with the smallest settlement units (up to 5,000 residents). In the event of a complete breach of stopbanks, the adverse effects for temporal accessibility of provincial capitals are quite evident in the water region of the Middle Vistula. This disruption to temporal accessibility is the most pronounced among all flood scenarios considered so far and the most evident among all other areas covered by these simulations.

6.2.2. The Oder River basin

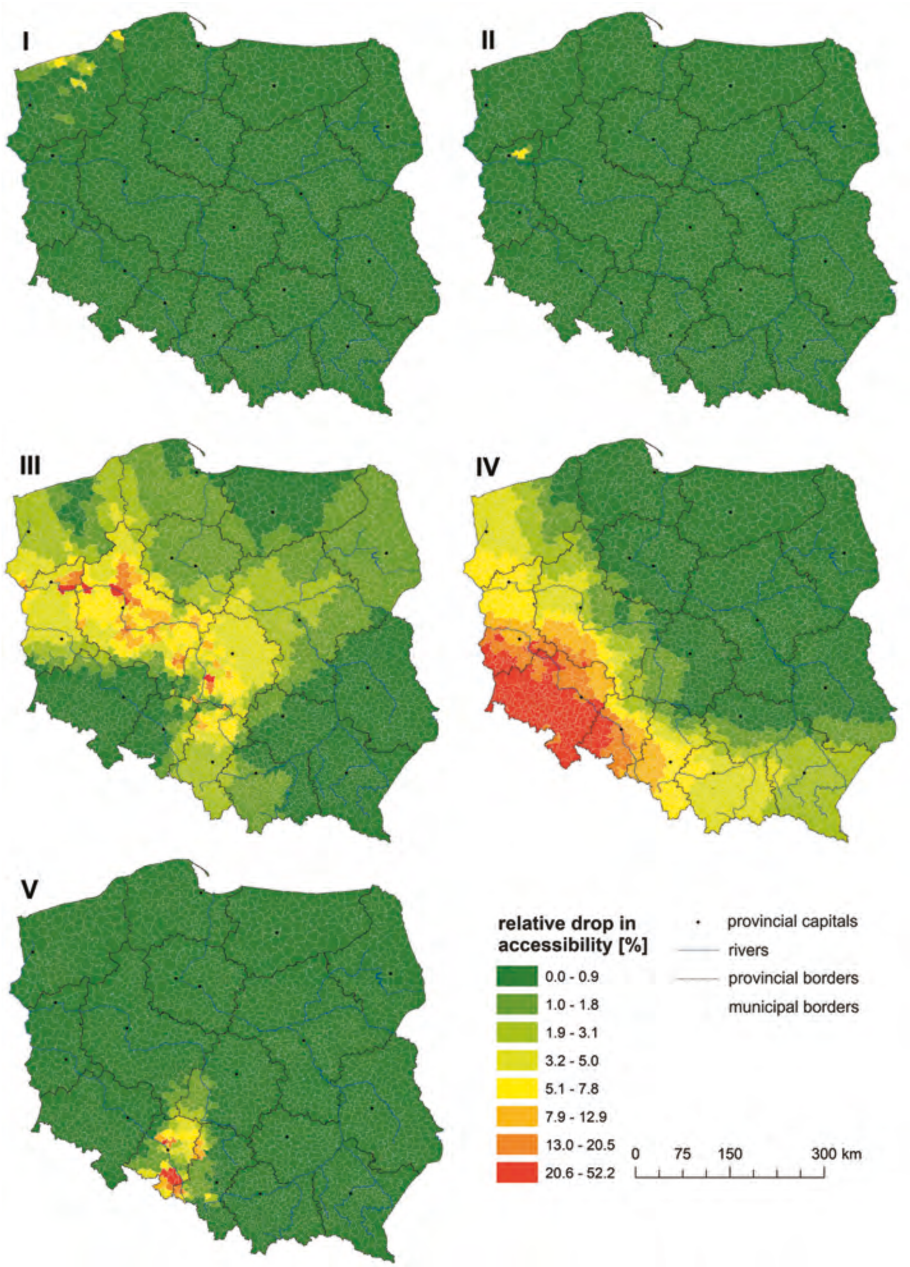
When long trips are incorporated into analyses of the impact that a flood would have on transport accessibility, it is evident that (within the Oder basin) the inundation of sections of the road network in the water regions of the Warta and the Middle Oder would endanger transport equilibrium. The location of flooded sections in the supra-local and supra-regional road network would cause spatially extensive, adverse effects on the potential accessibility of transport regions across Poland. In the event of a flood with a 10% probability of occurrence, due to the relatively small area at risk of inundation, the affected population residing there would also be small, which means that the decline in the attractiveness of transport regions would also not reach high values either. While the highest relative changes in the potential accessibility of individual transport regions are primarily observed within the water region of the Middle Oder, the widest spatial scope of drops (albeit very small) would be caused by a flood in the water region of the Warta (Figure 6.21), where the main disruption is to the transport component.



I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 6.21. Relative drops in potential transport accessibility for long trips due to a flood with a 10% probability of occurrence in the Oder basin by water region in Poland in 2019

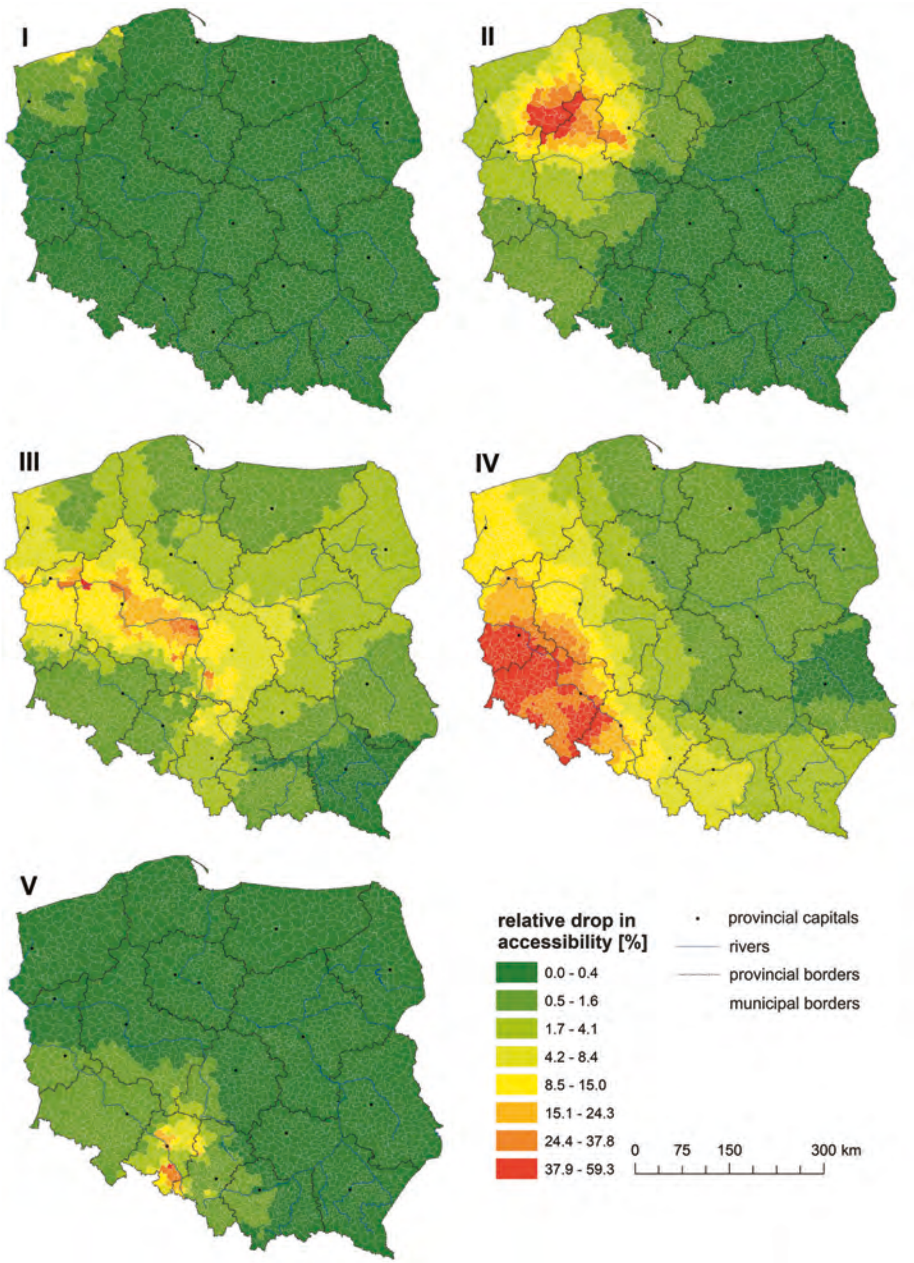
Source: own elaboration



I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 6.22. Relative drops in potential transport accessibility for long trips due to a (fluvial) flood with a 1% probability of occurrence in the Oder basin by water region in Poland in 2019

Source: own elaboration

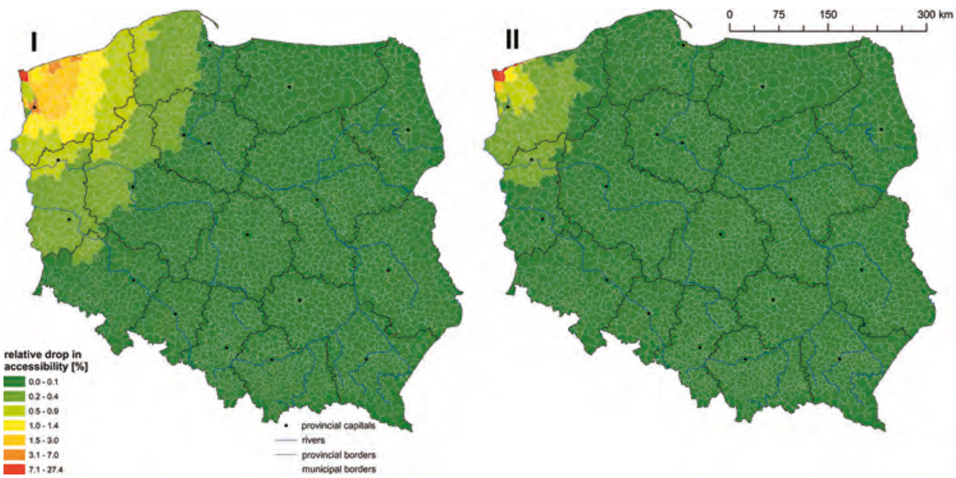


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 6.23. Relative drops in potential transport accessibility for long trips following a flood due to a complete breach of stopbanks in the Oder basin by water region in Poland in 2019

Source: own elaboration

In the scenarios for a flood with a 1% probability of occurrence and a complete breach of stopbanks, the importance of the land use component for the high and widespread drops in accessibility observed grows dynamically, mainly for Lower Silesia (Figures 6.22 and 6.23). In the scenario where there is a breach of stopbanks, the transport component also has a major impact on the relative drops in potential accessibility for the borderland between Greater Poland and West Pomerania. Although the localised drops in potential may even exceed 1/3 of the initial accessibility of the transport regions there, on a national scale these are comparable to the effects of the 10-year flood in the water region of the Warta (Figure 6.25).



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 6.24. Relative drops in potential transport accessibility for long trips following a flood in a given scenario in the water region of the Lower Oder and the coastal strip of the West Pomerania in Poland in 2019

Source: own elaboration

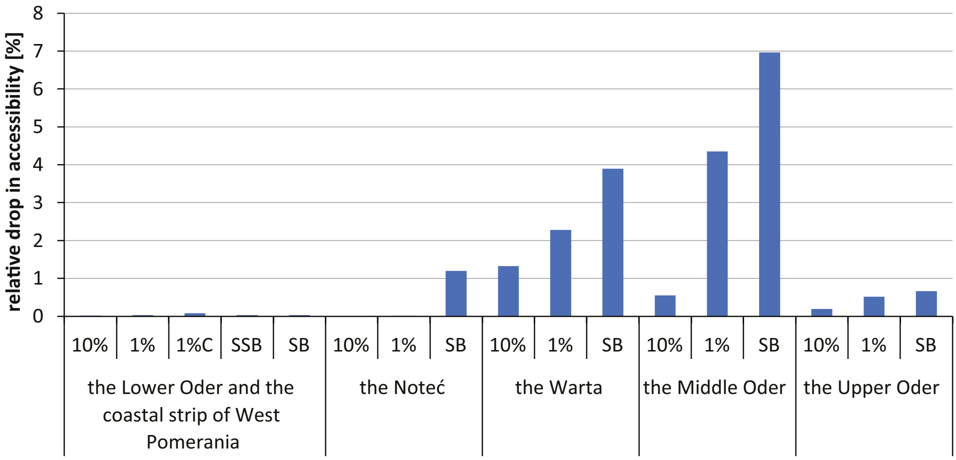


Figure 6.25. Relative drops in potential transport accessibility on a national scale for long trips due to a flood in a given scenario in the Oder basin by water region in Poland in 2019

Source: own elaboration

A flood in the water regions of the Lower Oder and the coastal strip of the West Pomerania (for all scenarios), and the Noteć barely affects the temporal accessibility of provincial capitals from settlement units. However, the analysis based on changes in polycentric isochrones of travel times to these cities reveals that a flood in the water regions of the Warta and (especially) the Middle Oder is not without effect on the spatial cohesion of the settlement network. It also shows that while the potential accessibility of the transport regions is not significantly deteriorated by flooding in the water region of the Upper Oder, the disruption to the road network in this area significantly increases the travel time to the provincial capital, especially for settlement units with a population from 5,000 to 20,000 (Table 6.5).

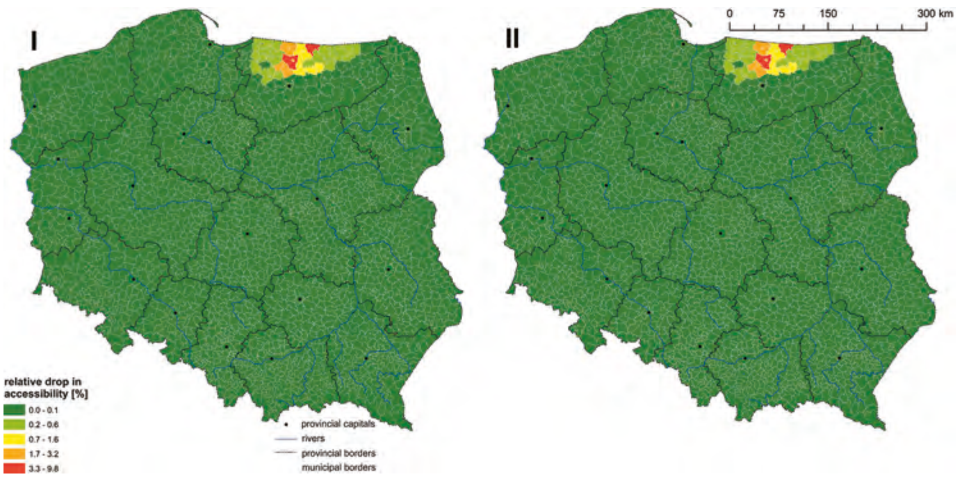
Table 6.5. Relative changes in the number of affected settlement units and the population residing there in the 30-minute intervals of travel time to provincial capitals due to a complete breach of stopbanks in the Oder basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Oder and the coastal strip of West Pomerania	0–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.06	0.00	0.00	0.00	0.00
	60–90	settlement units	–0.04	–0.24	0.00	0.00	0.00
		population	–0.03	–0.36	0.00	0.00	0.00
	90–120	settlement units	0.01	0.24	–0.74	0.00	0.00
		population	0.03	0.36	–1.08	0.00	0.00
the Noteć	0–30	settlement units	–0.07	–0.24	0.00	0.00	0.00
		population	–0.14	–0.22	0.00	0.00	0.00
	30–60	settlement units	–0.53	–0.94	0.00	0.00	0.00
		population	–0.44	–0.91	0.00	0.00	0.00
	60–90	settlement units	–0.12	0.94	0.00	0.00	0.00
		population	–0.05	0.98	0.00	0.00	0.00
	90–120	settlement units	–0.08	–0.47	–0.74	0.00	0.00
		population	0.07	–0.60	–0.61	0.00	0.00
the Warta	0–30	settlement units	–0.18	–0.94	0.00	0.00	–2.63
		population	–0.22	–0.85	0.00	0.00	–4.98
	30–60	settlement units	–1.17	0.00	–1.48	–2.13	0.00
		population	–1.00	–0.17	–1.61	–1.62	0.00
	60–90	settlement units	–0.75	0.71	–0.74	2.13	2.63
		population	–0.29	0.86	–0.63	1.62	4.98
	90–120	settlement units	2.01	0.24	2.22	0.00	0.00
		population	1.44	0.16	2.25	0.00	0.00
the Middle Oder	0–30	settlement units	–0.35	–0.71	–1.48	0.00	0.00
		population	–0.41	–0.65	–1.39	0.00	0.00
	30–60	settlement units	–1.61	–2.12	–1.48	–2.13	0.00
		population	–1.79	–2.00	–1.83	–3.11	0.00
	60–90	settlement units	–0.05	0.47	–2.96	–2.13	0.00
		population	–0.28	0.77	–2.14	–2.29	0.00
	90–120	settlement units	1.52	0.94	4.44	4.26	0.00
		population	1.87	0.56	3.65	5.41	0.00
the Upper Oder	0–30	settlement units	–0.20	–0.94	0.00	0.00	0.00
		population	–0.49	–0.82	0.00	0.00	0.00
	30–60	settlement units	–0.78	–0.24	–2.96	0.00	0.00
		population	–0.81	–0.17	–3.00	0.00	0.00
	60–90	settlement units	0.18	0.24	2.22	–2.13	0.00
		population	0.35	0.03	2.50	–1.69	0.00
	90–120	settlement units	0.79	0.71	0.74	2.13	0.00
		population	0.96	0.81	0.51	1.69	0.00

Source: own elaboration.

6.2.3. The Pregolya River basin

Potential-based analyses of changes in transport accessibility reveal that the operation of the road transport would barely be disrupted in water regions of the Łyna and the Węgorapa, regardless of the adopted flood probability.



I – 10% probability, II – 1% probability

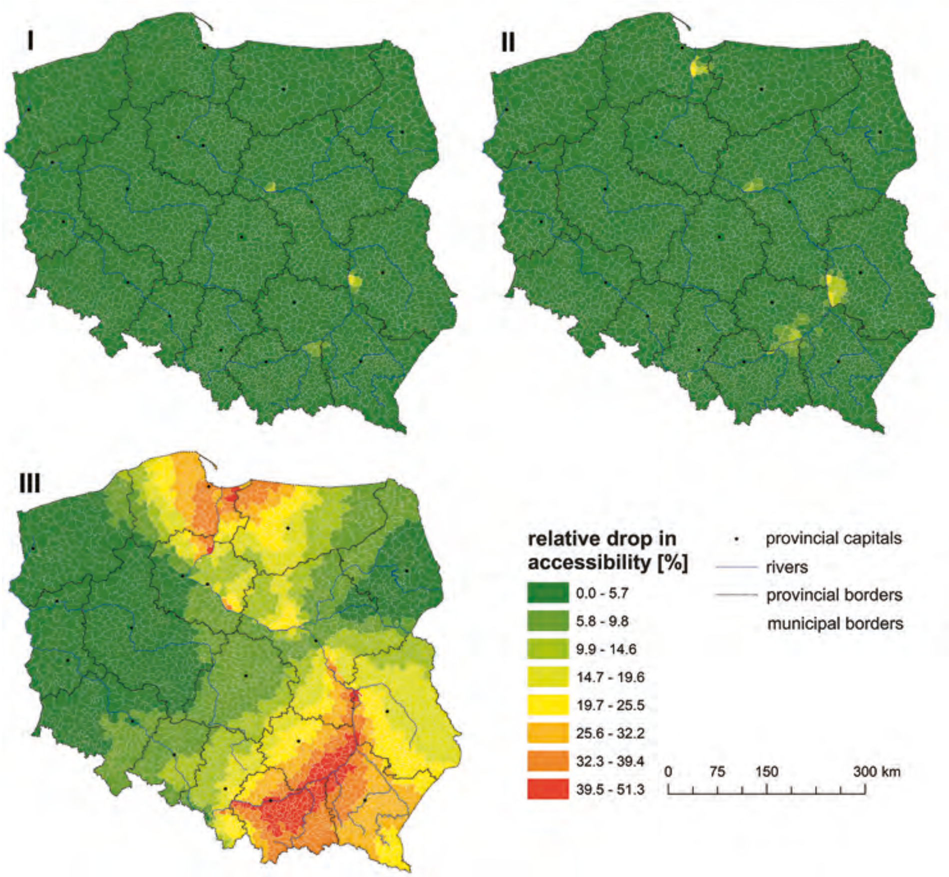
Figure 6.26. Relative drops in potential transport accessibility for long trips following a flood in a given scenario in the water region of the Łyna and the Węgorapa in Poland in 2019

Source: own elaboration

For long trips, disruptions to the road network and the attractiveness of the transport regions under the analysed flood scenarios for the Pregolya basin cause a maximum decrease in accessibility of just a few percent and then only for a small number of municipalities in Warmian-Masurian Province, whereas on a national scale this reduction amounts to 0.01% of the initial potential of transport accessibility.

6.2.4. Main rivers

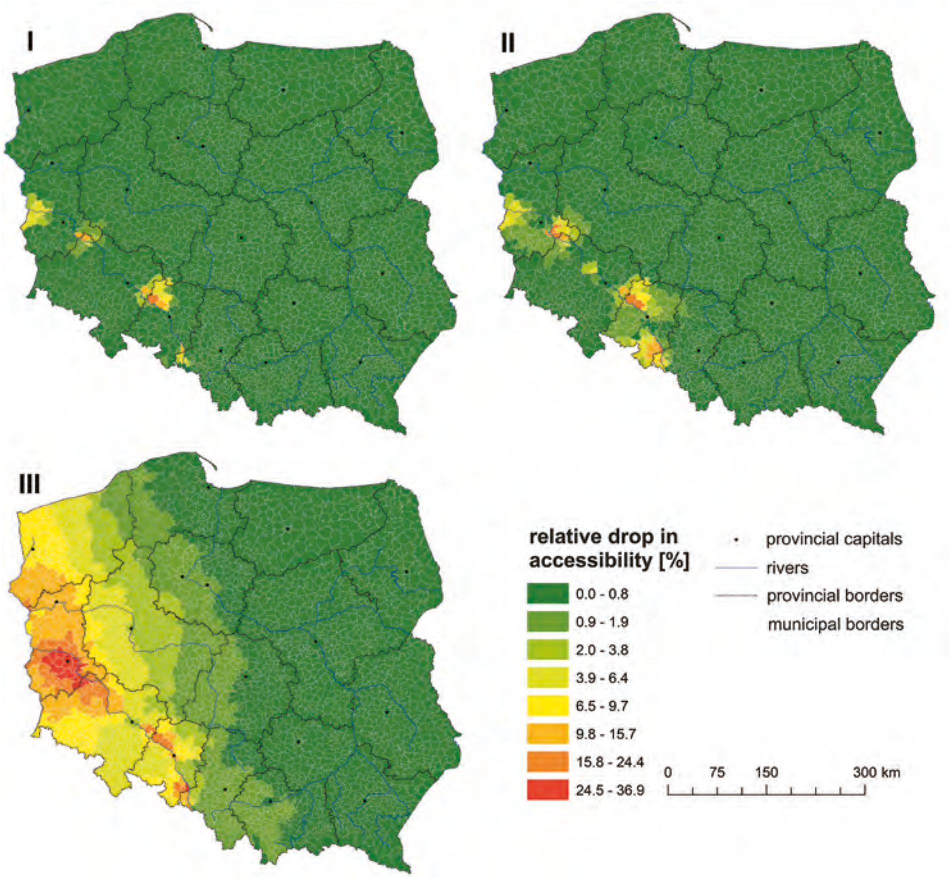
Simulations for short trips based on scenarios where a flood occurs on the main rivers indicate that a deterioration in potential accessibility on a national scale is observed only as a result of flooding on the Warta, again regardless of the adopted flood probability. These increases are small, not exceeding 1.5 percentage point, but given the lower values of the maximum drops in accessibility at the level of transport regions, they still confirm the greater spatial scope of the phenomenon for long trips (Figures 6.27–6.29). For these trips, a flood on the Warta is particularly concerning. This stems from the location of the road network sections susceptible to flooding within the areas at risk and the relevance of these sections to supra-local travel, mainly as a result of the route taken by the road infrastructure in the areas affected.



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 6.27. Relative drops in potential transport accessibility for long trips following a flood in a given scenario on the Vistula in Poland in 2019

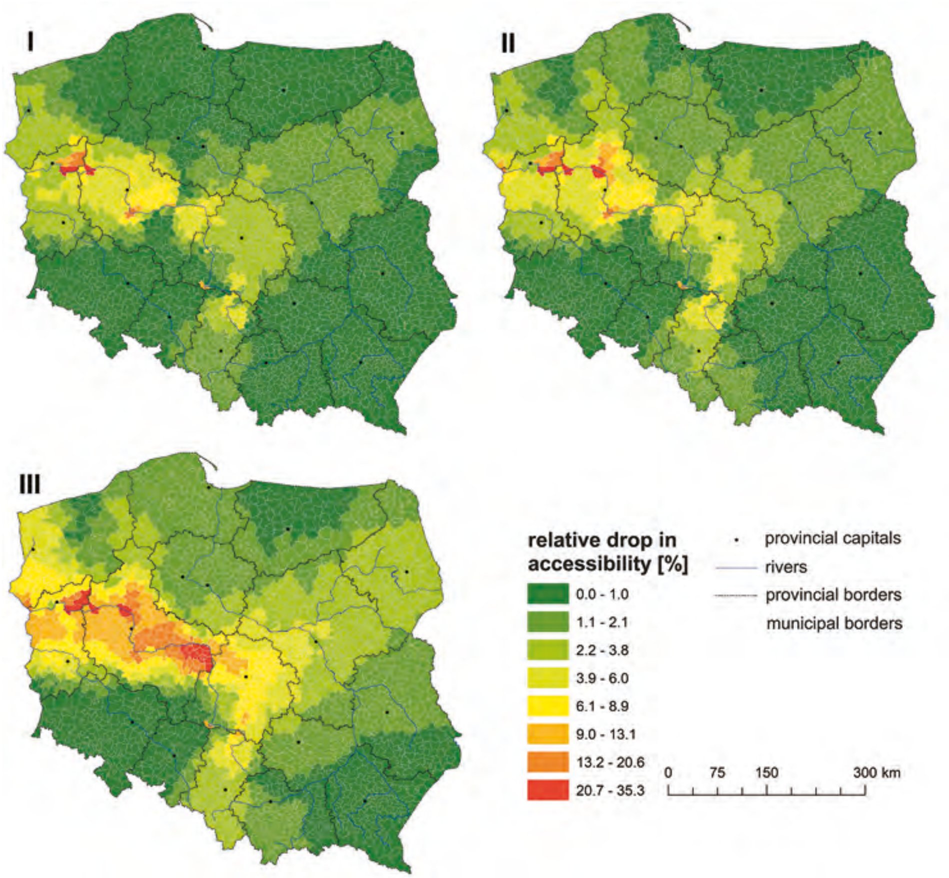
Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 6.28. Relative drops in potential transport accessibility for long trips following a flood in a given scenario on the Oder in Poland in 2019

Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 6.29. Relative drops in potential transport accessibility for long trips following a flood in a given scenario on the Warta in Poland in 2019

Source: own elaboration

When compared to short trips, the greatest increment in relative decreases in potential accessibility for long trips (over three percentage points) is observed for the scenario where there is a breach of stopbanks on the Vistula (Figure 6.30). Then, the drop is exacerbated by the co-occurrence of the following factors: the large and spatially concentrated set of transport regions experiencing a major drop in internal weights; the high level of potential accessibility they boast under "normal" conditions; and the road infrastructure unaffected by flooding which keeps them effectively connected (national roads: 19, 55, 79, 92; motorways: A4, A1). As regards the transport component, the large number of adjacent transport regions with impassable local road networks prevents some trips from being taken, especially those whose origin and destination are close to the inundated transport regions, yet far from each other. Given the scale of possible traffic disruptions following a flood on the Vistula due to a complete breach of stopbanks (mainly in its upper reaches), the accompanying increases in travel time may visibly reduce potential accessibility, notwithstanding the distance decay that is typical of long trips.

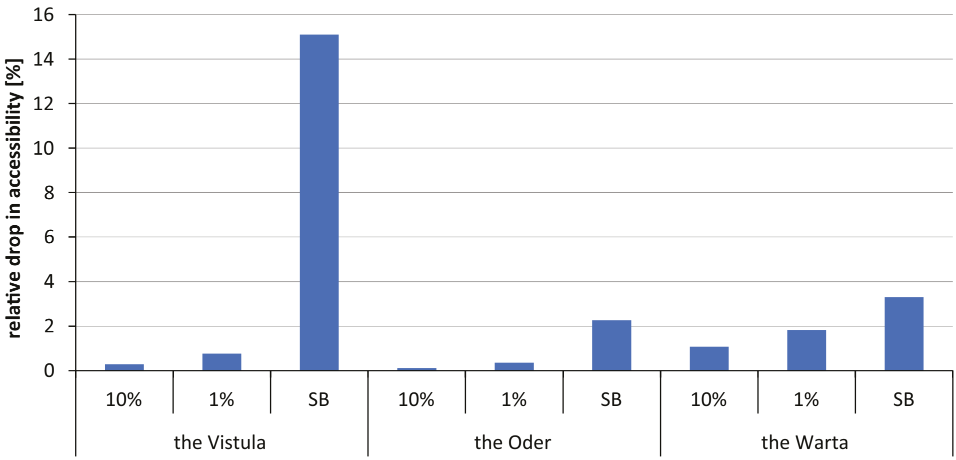


Figure 6.30. Relative drops in potential transport accessibility on a national scale for long trips due to a flood in a given scenario on the main rivers in Poland in 2019

Source: own elaboration

As regards transport accessibility to provincial capitals in Poland, neither a 10-year nor a 100-year flood on the Vistula would pose a major barrier. If either of these flood scenarios occurred on the Warta, however, the size of the area at risk of flooding would become an obstacle, and increases in travel times would affect a range of settlement units of different sizes (Table 6.6).

Table 6.6. Relative changes in the number of affected settlement units and the population residing there in the 30-minute intervals of travel time to provincial capitals due to a complete breach of stopbanks following a flood on the main rivers in Poland in 2019 [%]

River	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	**5,001 to 20,000**	**20,001 to 50,000**	**50,001 to 100,000**	**over 100,000**
			relative changes [%]				
the Vistula	0–30	settlement units	–1.17	–3.77	–5.93	–2.13	–5.26
		population	–2.74	–4.35	–5.25	–1.81	–22.78
	30–60	settlement units	–5.82	–7.55	–8.89	–4.26	–7.89
		population	–7.76	–7.65	–9.32	–3.50	–3.91
	60–90	settlement units	–3.26	–1.65	1.48	–2.13	7.89
		population	–2.15	–0.34	0.91	–3.21	18.09
	90–120	settlement units	6.08	7.08	8.15	6.38	2.63
		population	6.24	7.83	8.06	6.66	1.65
the Oder	0–30	settlement units	–0.31	–1.18	–0.74	0.00	0.00
		population	–0.52	–1.20	–0.51	0.00	0.00
	30–60	settlement units	–1.27	–0.24	–1.48	0.00	0.00
		population	–1.39	–0.13	–1.92	0.00	0.00
	60–90	settlement units	0.58	0.71	2.22	–2.13	0.00
		population	0.91	0.53	2.43	–1.69	0.00
	90–120	settlement units	1.00	0.47	0.00	2.13	0.00
		population	1.00	0.67	0.00	1.69	0.00
the Warta	0–30	settlement units	–0.15	–0.71	0.00	0.00	0.00
		population	–0.16	–0.59	0.00	0.00	0.00
	30–60	settlement units	–0.65	0.94	–1.48	–2.13	0.00
		population	–0.57	0.76	–1.61	–1.62	0.00
	60–90	settlement units	–0.27	–0.24	–0.74	2.13	0.00
		population	–0.07	–0.18	–0.63	1.62	0.00
	90–120	settlement units	1.07	0.00	2.22	0.00	0.00
		population	0.79	0.00	2.25	0.00	0.00

Source: own elaboration.

A dramatic change in accessibility to provincial capitals would be caused by a complete breach of stopbanks. As with the analyses of potential accessibility, the exclusion of some road network sections during a flood on the Vistula would also result in the greatest rises in travel time, but this time for settlement units of all sizes.

7

CHANGES IN ROAD NETWORK LOAD FOLLOWING FLOODS

7. 1. Commuting to work

The main patterns of changes in road network load from commuter traffic are determined by the key properties of the trips for this motivation. Increases and decreases in vehicle numbers for the flood simulations typically involve the inundated sections of the road network in the water region itself. This mainly stems from the fact that commuting mostly consists of short trips. Since there is a relatively short distance and travel time between the trip origin and destination in the event of a detour needed, there is always a spatially confined set of sensible diversions.

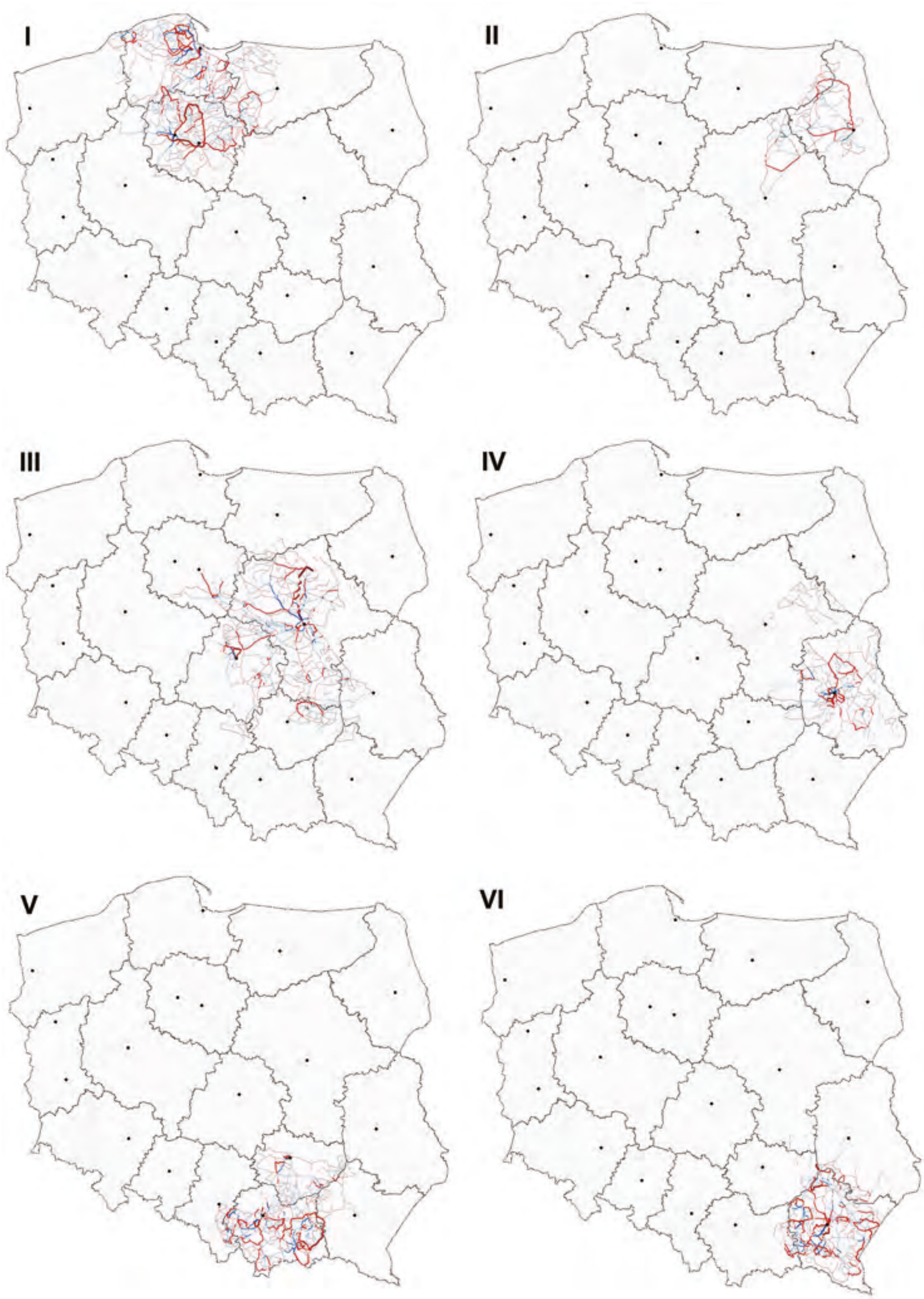
In contrast to long journeys (e.g., business trips), the alternatives available for short trips necessitate driving at low average speeds and thus entail increased travel time. Although there are alternative routes in some cases that use high-speed roads which are most resistant to flooding (e.g., sections of the A1 and A2 motorways during a breach of stopbanks in the water region of the Middle Vistula), a relatively large number of trip destinations of similar traffic-generating potential (municipalities where workplaces are located) are spread evenly across Poland forcing the majority of users to choose local road classes. The impact that the reduction in traffic potentials of the transport regions affected by flooding in a given scenario has on the number of trips is also noticeable on the network sections under flood simulation. This reduction visibly translates (albeit not so clearly as for business trips) into a drop in the growth of vehicle-kilometres arising from the necessity to choose a route that does not offer the minimum travel time to reach the destination. This is particularly pronounced during a complete breach of stopbanks, when the said reductions reach the highest values and disruptions to the transport network are most severe. Analyses of the susceptibility of the road network to inundation shows a distinct exacerbation in those scenarios where the scope of the flood's impact increases (especially during a complete breach of stopbanks).

Changes in vehicle-kilometres when the simulated flood impacts a larger area are not as evident, since there occurs a "flattening" of these increments due to the increasing length of network sections being taken out of service. However, this correlation is by no means linear, but conditioned by a number of factors, whose impact varies greatly in the different flood scenarios and for the different areas under study. This variability applies to two components: transport and land use. It is only when these are "superimposed" that the returned results give a picture of changes in the distribution of traffic over the network and the volumes of vehicle-kilometres. As regards the transport component, it is not the exposure of a given network section that matters, but how crucial it is for the completion of commuter trips between transport regions within the analysed areas. For the component of land use (here: traffic-generating potential), the absolute magnitude of the decrease in vehicle traffic resulting from the reduction in this potential depends both on the severity of the flood and the role of a given municipality in the labour market (how many employees commute to and from it). The said "flattening" of vehicle-kilometres stems both from a reduction in the volume of deferred traffic following a general drop in the number of trips taken, and from the distribution of road network segments exposed to flooding. Road closures accompanying a flood that spreads over a large area mainly affect the same road network segments but over longer distances. A significant rise in the length of the road section that may be inundated when a flood's range increases does not automatically translate into a directly proportional drop in the number of vehicles that originally travelled along it, since this section has already lost its "attractiveness" once just a short stretch was inundated in the early stages of the flood.

For the spatial distribution of changes in road network load, the type of data used to distribute traffic on the network is critical. The employment of matrix data on actual commuting noticeably reduces the spatial scope of the changes in road network load compared to a model-based approach (applied, inter alia, for analysing business trips).

7.1.1. The Vistula River basin

The largest spatial scope of changes in road network load caused by commuter traffic in the scenario of a fluvial flood is observed for the water region of the Middle Vistula (Figures 7.1–7.3). This is due to both the size of the region itself (the largest among all areas under study) and the fact that the largest labour market in Poland is located there (the city of Warsaw). In addition, flooding in the area would result in changes in vehicle numbers on the road network in the largest number of provinces.


I
II
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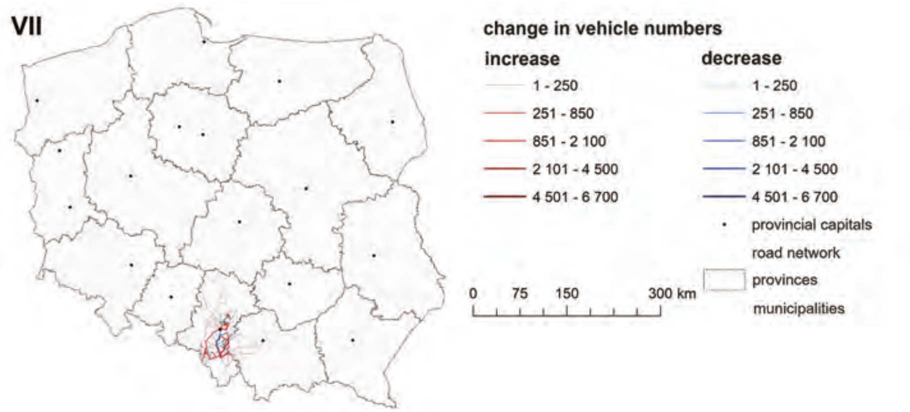
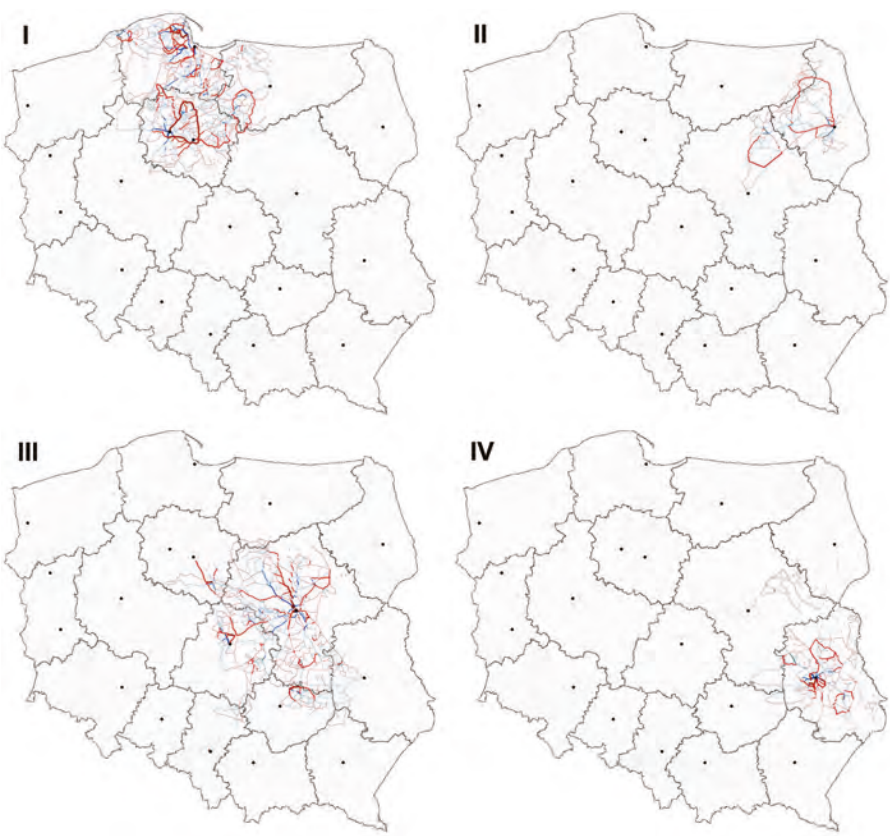
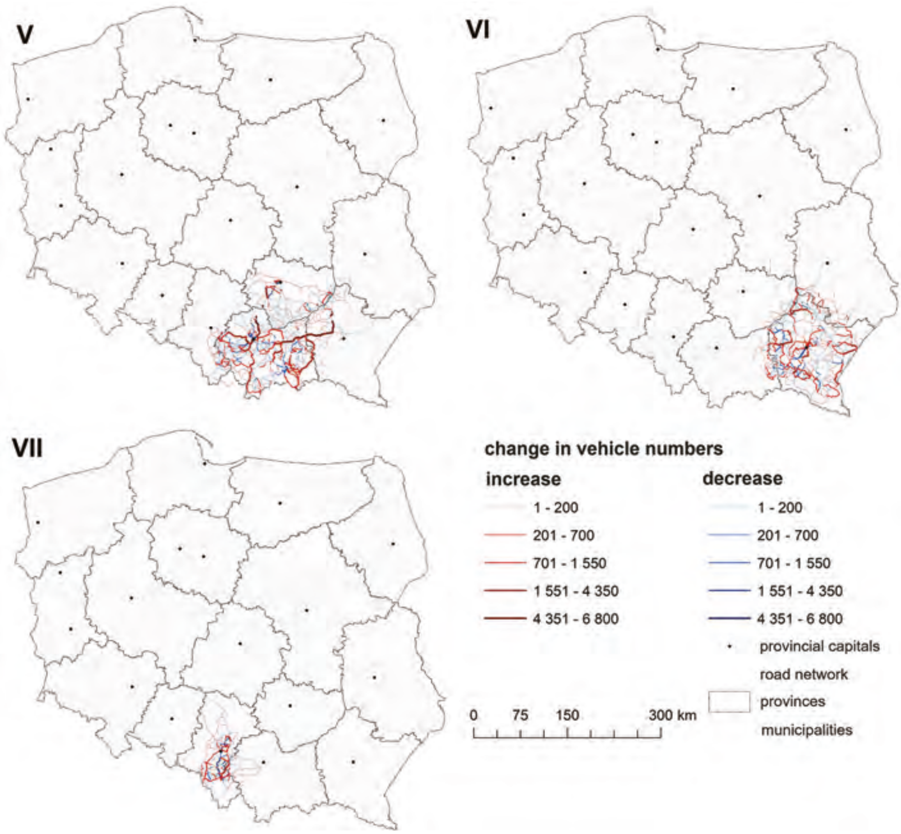


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 7.1. Changes in road network load for commuting to work due to a flood with a 10% probability of occurrence within the Vistula basin by water region in Poland in 2019

Source: own elaboration

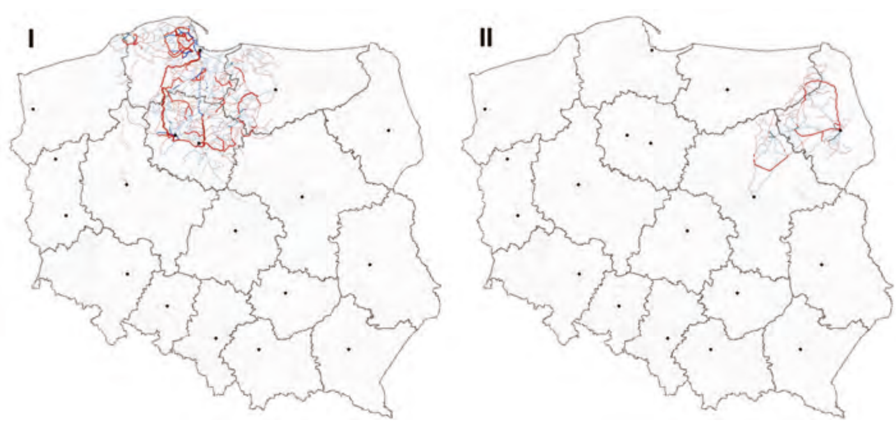


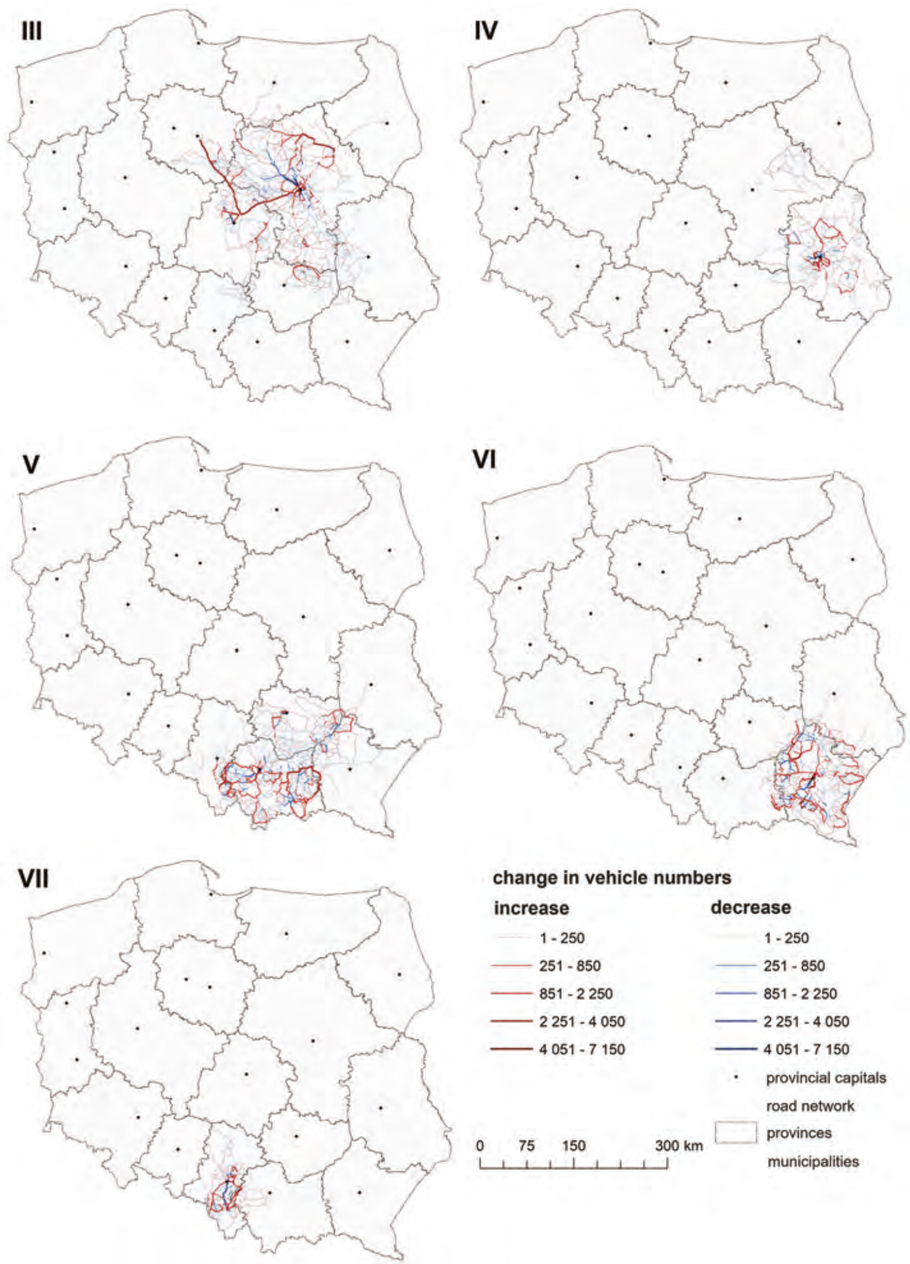


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 7.2. Changes in road network load for commuting to work due to a (fluvial) flood with a 1% probability of occurrence within the Vistula basin by water region in Poland in 2019

Source: own elaboration



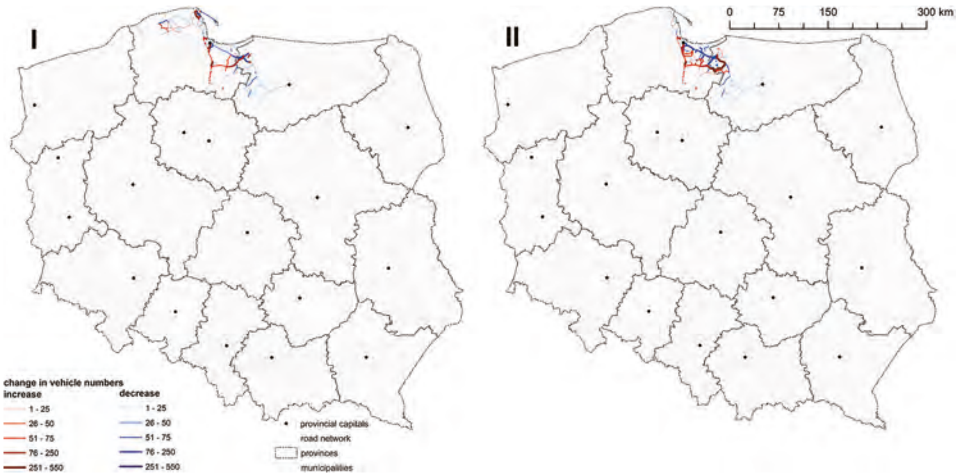


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug, V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 7.3. Changes in road network load for commuting to work following a flood due to a complete breach of stopbanks within the Vistula basin by water region in Poland in 2019

Source: own elaboration

The effects of a coastal flood (Figure 7.4) on road transport and commuting are far less severe than in any scenario that involves a fluvial flood.



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 7.4. Changes in road network load for commuting to work due to a flood in a given scenario within the water region of the Lower Vistula in Poland in 2019

Source: own elaboration

The magnitude of the changes in the impact that a flood would have on commuter trips by passenger car in the different scenarios is well illustrated by the increases and decreases in vehicle-kilometres resulting from the necessity to switch from the optimum travel paths available in "normal" conditions to a route that only becomes optimum during a flood (Figure 7.5). Particularly burdensome for the national road transport network would be floods in three water regions: the Upper Western Vistula, the Middle Vistula, and the Lower Vistula. This load does not, however, exceed 15% of the total volume of vehicle-kilometres for commuting in Poland. When the returned results are juxtaposed against the spatial scope of individual water regions, it transpires that the most disruptive situation would be in the water region of the Upper Vistula, where the relatively small increments in vehicle-kilometres are observed between the different scenarios.

In the scenario of a total breach of stopbanks within the water region of the Lower Vistula, the rise in vehicle-kilometres is smaller than for the scenario of a flood with a 1% probability of occurrence. This stems from the high reduction in the traffic-generating potential of the transport regions that would be flooded following a breach of stopbanks, e.g., within the Vistula Fens. In addition, the Lower Vistula area boasts road infrastructure (the S7 expressway), which is highly resistant to flooding, visibly enhancing the possibility of making a journey (especially between transport regions which are not directly affected by a flood in this scenario). The situation is similar for the simulation of flooding in the water region of the Upper Western Vistula. What stands out here is the pronounced difference between increases in the number of vehicle-kilometres for floods with a medium and a high probability of occurrence.

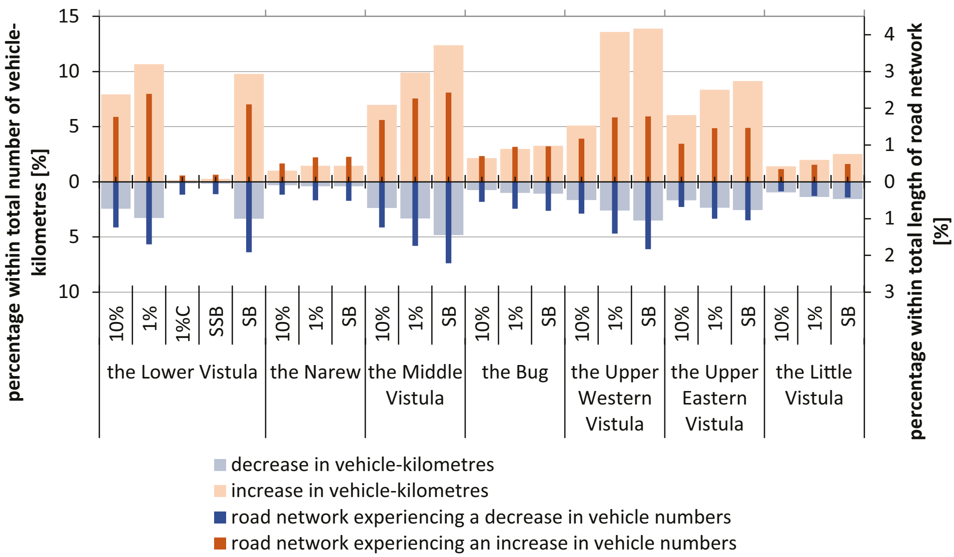


Figure 7.5. Relative changes in the number of vehicle-kilometres for commuting to work following a flood in a given scenario within the Vistula basin by water region in Poland in 2019

Source: own elaboration

Important information on the impact that floods may have on road transport is also gathered when one analyses the structure of changes in the number of vehicle-kilometres by road category on those roads affected by an absolute increase or decrease in traffic flow volumes (Table 7.1).

Table 7.1. Structure of changes in the number of vehicle-kilometres by road category for commuting due to a flood in a given scenario in the Vistula basin by water region in Poland in 2019

Water region	Flood scenario	Change	Road category						
			motorway (%)	express-way (%)	national (%)	regional (%)	district (%)	municipal (%)	other (%)
1	2	3	4	5	6	7	8	9	10
the Little Vistula	SB	increase	7.1	6.9	18.7	39.0	24.3	3.8	0.2
the Little Vistula	SB	decrease	3.3	7.1	69.8	10.7	7.5	1.4	0.0
the Little Vistula	1%	increase	4.9	8.3	23.7	29.9	30.2	2.6	0.3
the Little Vistula	1%	decrease	3.9	7.8	67.0	11.6	8.1	1.5	0.0
the Little Vistula	10%	increase	5.2	7.8	27.5	27.8	29.0	2.4	0.3
the Little Vistula	10%	decrease	4.2	9.1	66.2	10.9	7.9	1.6	0.0
the Upper Eastern Vistula	SB	increase	10.8	1.8	12.9	21.9	47.1	4.8	0.6
the Upper Eastern Vistula	SB	decrease	0.1	0.2	49.1	30.8	18.4	1.4	0.0
the Upper Eastern Vistula	1%	increase	13.8	1.7	10.9	21.2	48.3	3.5	0.6
the Upper Eastern Vistula	1%	decrease	0.1	0.1	48.3	30.6	19.4	1.5	0.0
the Upper Eastern Vistula	10%	increase	9.3	0.7	11.1	26.6	48.3	3.7	0.3
the Upper Eastern Vistula	10%	decrease	1.0	3.1	50.9	25.9	17.6	1.5	0.0
the Upper Western Vistula	SB	increase	13.6	1.9	27.0	23.3	30.0	4.0	0.2
the Upper Western Vistula	SB	decrease	3.0	3.9	35.6	38.2	15.2	4.0	0.0
the Upper Western Vistula	1%	increase	27.3	2.2	24.5	22.6	18.6	4.6	0.1
the Upper Western Vistula	1%	decrease	3.0	4.5	39.7	35.6	13.8	3.3	0.1
the Upper Western Vistula	10%	increase	9.8	2.2	27.3	22.9	32.0	5.7	0.2
the Upper Western Vistula	10%	decrease	2.8	5.1	32.6	38.9	16.6	4.0	0.0
the Bug	SB	increase	0.1	14.8	11.3	28.4	42.1	3.0	0.2
the Bug	SB	decrease	0.0	8.5	35.8	42.0	11.8	1.7	0.3
the Bug	1%	increase	0.0	14.2	12.2	30.1	40.4	2.9	0.2
the Bug	1%	decrease	0.0	8.6	37.1	41.1	11.2	1.7	0.3
the Bug	10%	increase	0.0	13.9	13.0	30.6	39.3	3.0	0.2
the Bug	10%	decrease	0.0	8.5	37.6	40.5	11.4	1.7	0.3
the Middle Vistula	SB	increase	41.1	6.3	18.8	14.4	16.8	2.3	0.4
the Middle Vistula	SB	decrease	0.7	8.9	51.0	28.2	9.3	1.7	0.2
the Middle Vistula	1%	increase	15.5	9.4	21.9	28.3	20.6	3.6	0.7
the Middle Vistula	1%	decrease	1.9	9.6	44.3	32.6	9.7	1.7	0.3
the Middle Vistula	10%	increase	8.8	4.8	30.8	22.8	29.1	3.2	0.5
the Middle Vistula	10%	decrease	2.1	8.9	44.9	31.9	10.4	1.4	0.3
the Narew	SB	increase	0.0	23.9	35.7	26.5	8.5	4.6	0.8
the Narew	SB	decrease	0.0	1.6	53.8	34.8	6.6	2.9	0.2
the Narew	1%	increase	0.0	23.5	35.6	27.0	8.5	4.6	0.8
the Narew	1%	decrease	0.0	1.6	54.1	34.5	6.7	3.0	0.2
the Narew	10%	increase	0.0	22.5	37.0	25.8	9.0	4.9	0.8
the Narew	10%	decrease	0.0	1.5	54.1	34.5	6.6	3.0	0.2

Table 7.1 (cont.)

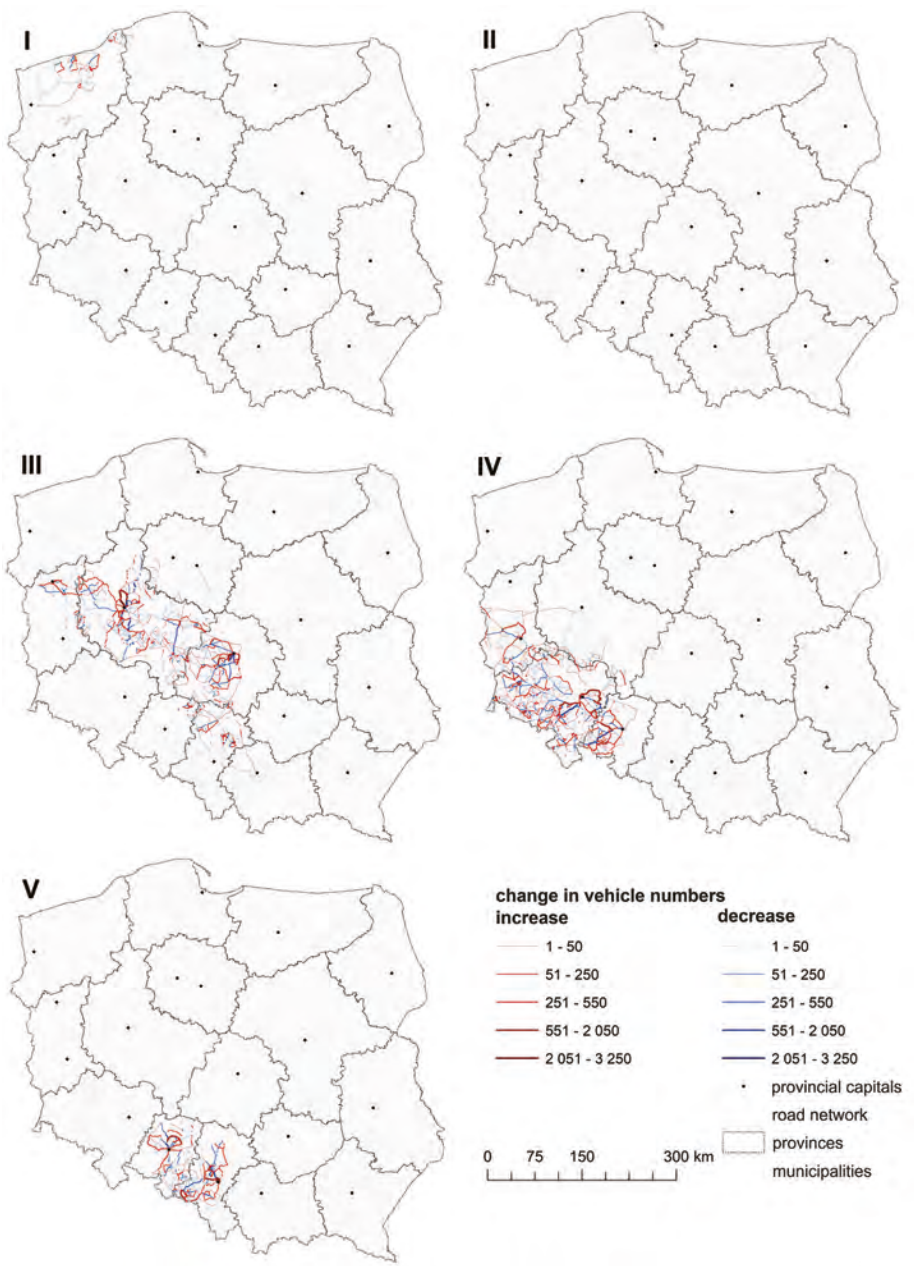
1	2	3	4	5	6	7	8	9	10
the Lower Vistula	SB	increase	8.7	4.3	14.2	30.6	30.2	11.5	0.4
		decrease	4.0	7.5	55.5	19.9	10.4	2.4	0.2
	SSB	increase	17.1	19.7	14.4	14.1	17.5	16.7	0.5
		decrease	0.1	34.4	25.0	15.6	19.3	5.0	0.6
	1%C	increase	24.8	12.2	30.1	17.5	10.7	4.7	0.0
		decrease	0.1	26.8	6.0	31.6	33.2	2.0	0.3
	1%	increase	12.4	6.3	22.4	17.6	32.0	8.8	0.6
		decrease	0.3	6.1	61.7	20.3	9.1	2.3	0.2
	10%	increase	12.1	6.1	22.9	17.8	31.8	8.8	0.5
		decrease	0.3	6.1	61.6	20.5	9.1	2.3	0.2

Source: own elaboration.

Here, the most important categories are national and regional roads; on average, they experience the greatest cumulative increases and decreases in vehicle numbers following a flood. It is also worth noting the high percentage values for motorways in servicing the increased traffic (higher numbers of vehicle-kilometres), especially during a complete breach of stopbanks within the water regions of the Upper Vistula and the Middle Vistula. This data could greatly assist the operators of the National Road Traffic Management System, a tool created to dynamically manage vehicle traffic in order to improve the safety of road users and the efficiency of road transport. With this data, the system could respond in real time to non-cyclical changes in traffic flow volumes and improve their efficient relocation.

7.1.2. The Oder River basin

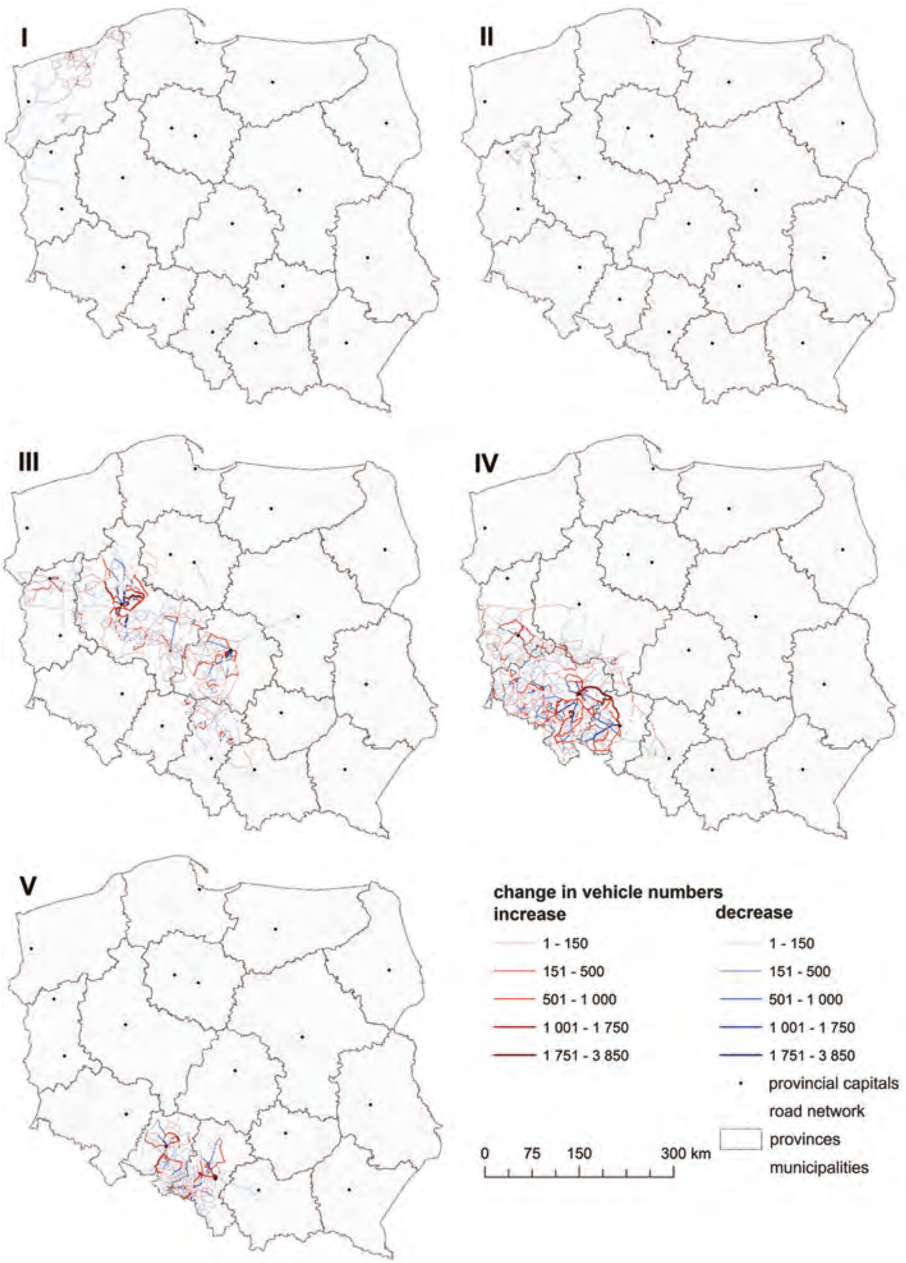
A flood in the water region of the Middle Oder would pose a particular threat to the equilibrium of the transport system as regards commuting to work (Figures 7.6–7.8). Although changes in road network load caused by flooding (in all scenarios) are visible there over a considerable area, these are not such far-reaching disturbances as, for instance, in the water region of the Middle Vistula. This arises from the fact that the labour market in the water region of the Middle Oder is not dominated by a single city as the main destination for commuter traffic. The spatial distribution of smaller towns and the two major cities (Wrocław and Zielona Góra) is more regular and the labour market of these two cities combined is considerably smaller than of Warsaw. When analysing maps of changes in road network load, one cannot ignore the situation in the water region of the Warta. While the spatial scope of changes in vehicle traffic flows is significant (due to the shape of the water region itself), their total volume is lower than in the regions discussed above. A flood in the water regions of the Lower Oder and the coastal strip of West Pomerania, and the Noteć would pose a relatively minor disruption to commuting by passenger car. For the latter, a noticeable disturbance to the equilibrium of the transport system only occurs during a complete breach of stopbanks.



I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 7.6. Changes in road network load for commuting to work due to a flood with a 10% probability of occurrence within the Oder basin by water region in Poland in 2019

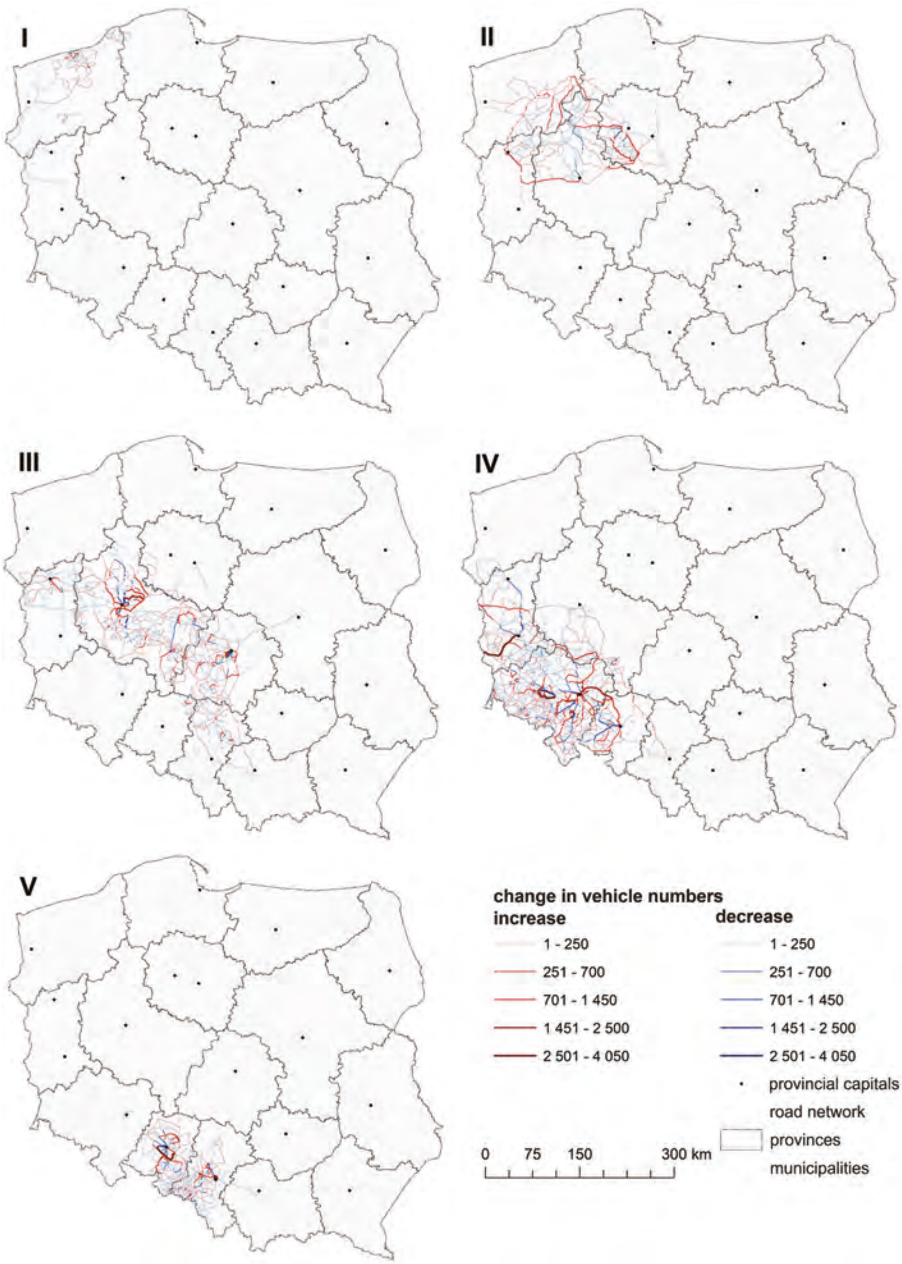
Source: own elaboration



I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 7.7. Changes in road network load for commuting to work due to a (fluvial) flood with a 1% probability of occurrence within the Oder basin by water region in Poland in 2019

Source: own elaboration

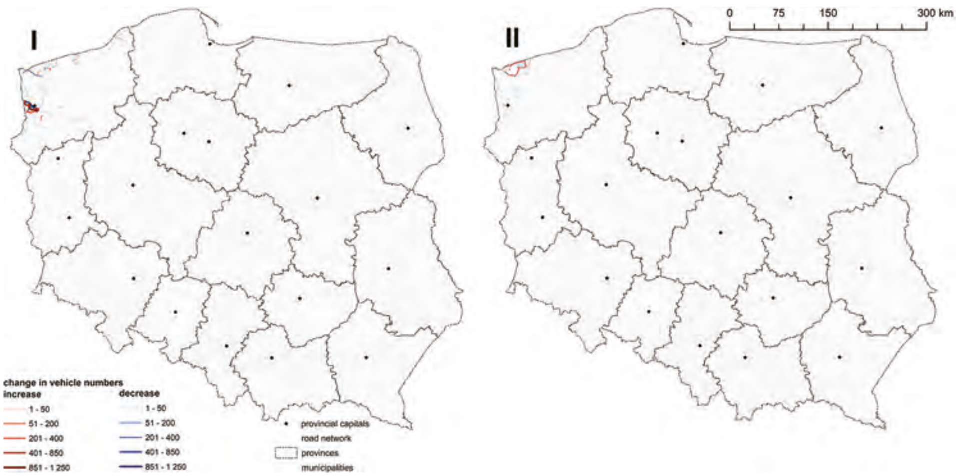


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć,
III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 7.8. Changes in road network load for commuting to work following a flood due to a complete breach of stopbanks within the Oder basin by water region in Poland in 2019

Source: own elaboration

When a coastal flood (Figure 7.9) is simulated to assess its impact on the transport network, it can be concluded that it would not pose a significant obstacle to commuting to work in Poland, as the spatial scope of the observed changes in road network load and their magnitude are limited.



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 7.9. Changes in road network load for commuting to work due to a flood in a given scenario within the water region of the Lower Oder and the coastal strip of West Pomerania in Poland in 2019

Source: own elaboration

Analyses of the changes in vehicle-kilometres following a flood for the different scenarios on the Oder confirm the worrying situation observed earlier, which may occur when a flood strikes in the water region of the Middle Oder (Figure 7.10). The circumstances following a complete breach of stopbanks there seem particularly impactful, as the increase in vehicle-kilometres would almost reach the value observed for the same scenario in the water region of the Middle Vistula. The Middle Oder is also the region where the intensification of the threat translates most sharply into increments in vehicle-kilometres.

In the event of a flood, regional roads are particularly important for commuter traffic in the basin of the Oder, as they account for the largest percentage of increases and decreases in traffic flows observed in the study (Table 7.2).

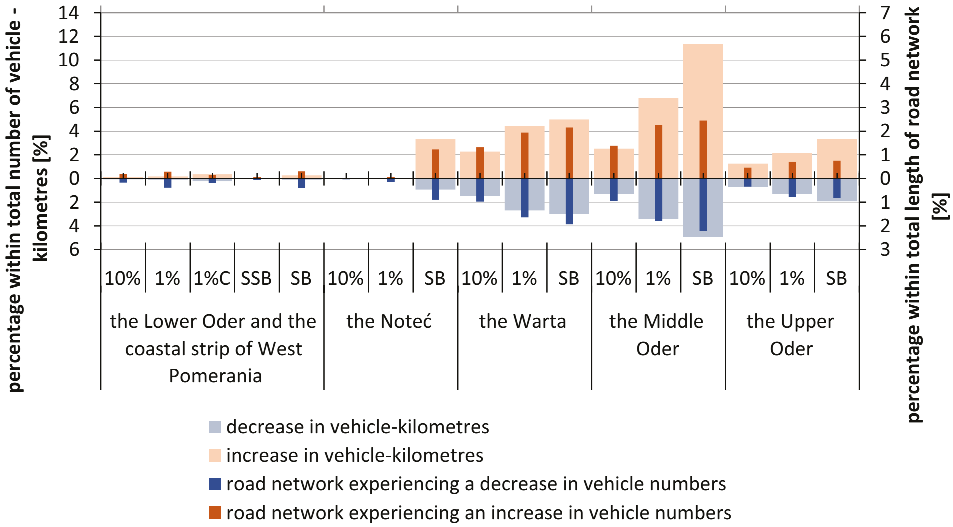


Figure 7.10. Relative changes in the number of vehicle-kilometres for commuting to work following a flood in a given scenario within the Oder basin by water region in Poland in 2019

Source: own elaboration

Table 7.2. Structure of changes in the number of vehicle-kilometres (by road category) for commuting due to a flood in a given scenario in the Oder basin by water region in Poland in 2019

Water region	Flood scenario	Change	Road category						
			motorway (%)	express-way (%)	national (%)	regional (%)	district (%)	municipal (%)	other (%)
1	2	3	4	5	6	7	8	9	10
the Upper Oder	SB	increase	31.8	0.2	21.0	18.2	26.7	1.5	0.7
		decrease	4.8	0.1	46.0	39.8	8.7	0.5	0.1
	1%	increase	21.8	0.3	29.4	25.5	20.1	2.2	0.7
		decrease	6.8	0.1	33.4	47.0	12.0	0.6	0.1
	10%	increase	23.0	0.4	36.2	20.8	17.9	0.9	0.9
		decrease	2.5	0.0	30.2	56.0	10.3	1.0	0.1
the Middle Oder	SB	increase	9.1	14.5	26.9	29.3	16.8	3.1	0.3
		decrease	18.6	12.2	35.9	22.2	9.3	1.3	0.4
	1%	increase	8.5	12.7	13.1	38.7	22.7	3.7	0.4
		decrease	9.5	1.6	45.7	29.2	11.9	1.5	0.6
	10%	increase	15.2	8.6	15.3	26.5	26.9	6.8	0.7
		decrease	5.3	2.8	44.9	31.0	13.5	1.7	0.8

Table 7.2 (cont.)

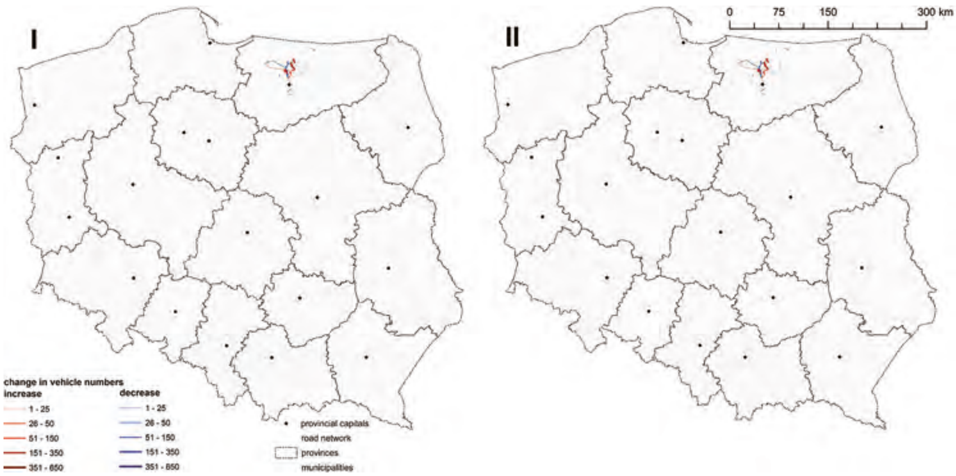
1	2	3	4	5	6	7	8	9	10
the Warta	SB	increase	6.4	10.1	13.2	33.4	27.5	8.6	0.8
		decrease	5.5	2.7	35.7	40.3	12.2	3.3	0.4
	1%	increase	8.1	10.1	13.4	34.6	24.8	8.2	0.7
		decrease	3.0	2.9	33.8	43.5	12.7	3.5	0.4
	10%	increase	8.3	5.9	20.0	35.3	21.7	7.4	1.3
		decrease	3.6	4.1	29.8	44.7	13.6	3.8	0.5
the Noteć	SB	increase	7.8	11.7	30.3	20.4	19.5	8.9	1.4
		decrease	0.1	2.3	37.1	42.1	12.1	4.5	1.8
	1%	increase	0.0	60.9	9.0	12.1	8.7	6.6	2.6
		decrease	0.0	2.2	1.0	55.5	13.9	13.4	14.0
	10%	increase	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		decrease	0.0	21.2	11.9	52.0	0.2	14.4	0.4
the Lower Oder and the coastal strip of West Pomerania	SB	increase	0.0	0.1	15.9	36.1	32.5	14.7	0.7
		decrease	0.6	4.1	21.8	45.3	24.1	3.8	0.3
	SSB	increase	0.0	0.1	6.1	70.5	17.5	5.2	0.6
		decrease	0.2	10.0	55.4	22.4	7.9	3.8	0.2
	1%C	increase	28.5	0.4	34.0	3.9	31.9	1.4	0.0
		decrease	3.4	1.9	47.3	22.5	18.0	6.9	0.0
	1%	increase	0.0	0.1	9.6	33.3	30.8	25.2	1.0
		decrease	0.4	4.2	21.3	52.7	17.2	3.8	0.3
	10%	increase	0.0	0.1	5.0	32.0	33.9	27.8	1.2
		decrease	0.0	4.6	23.9	49.0	18.0	4.1	0.3

Source: own elaboration.

In this regard, certain sections of national roads are marginally less important than regional roads. As for expressways and motorways, one must note the significance of the A4 motorway within the water region of the Upper Oder for vehicle traffic in all flood scenarios, and the A6 motorway during a coastal flood. The expressways (especially S3, S5, and S8) are important if there is a flood in the water region of the Middle Oder and the Warta.

7.1.3. The Pregolya River basin

A flood in the water region of the Łyna and the Węgorapa would only bring localised effects for commuter traffic (Figure 7.11). Due to the negligible number of commuter trips along the routes where there are road sections at risk of flooding, the observed changes in traffic flow volumes are limited. There is an even smaller change in the magnitude of vehicle flows as the area at risk expands, which can be explained by the minimal percentage of the area at risk within the transport regions affected by flooding in this water region and the very low number of the population at risk. This results in an almost imperceptible reduction in traffic-generating potentials.



I – 10% probability, II – 1% probability

Figure 7.11. Changes in road network load for commuting to work due to a flood in a given scenario within the water region of the Łyna and the Węgorapa in Poland in 2019

Source: own elaboration

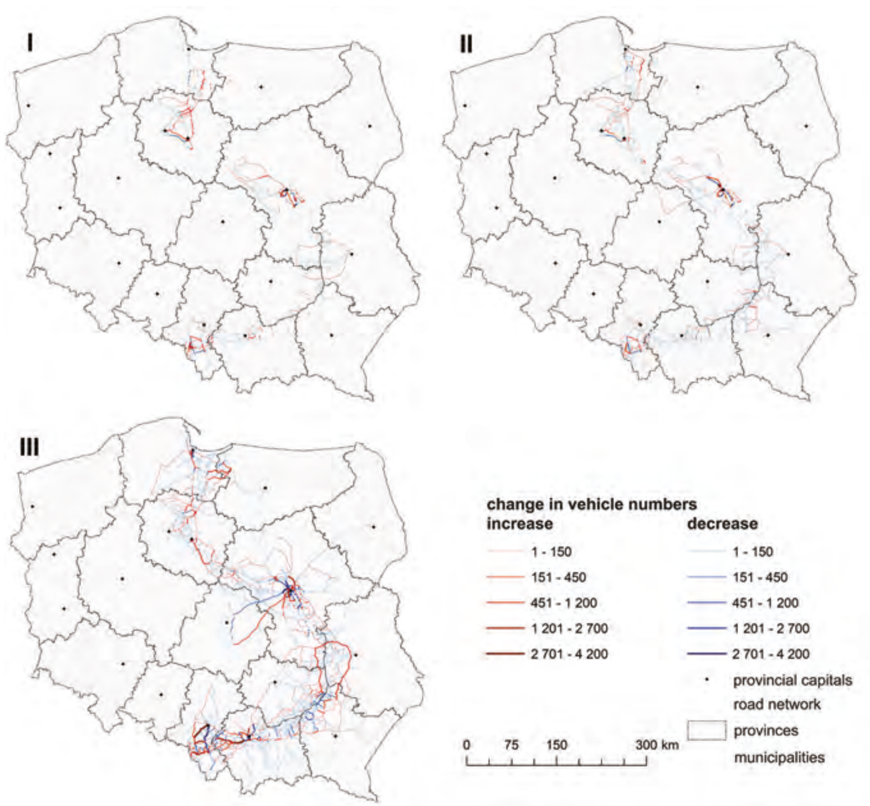
The exclusively localised nature of the changes in road network following a flood in the basin of the Pregolya is also confirmed by the increment in vehicle-kilometres for both the 1% and 10% flood probability. It never exceed 0.05% of the total volume of vehicle-kilometres for commuting to work. These extremely small changes in the equilibrium of the transport system pertain almost entirely to the local road infrastructure. The predominant percentage (almost 90%) of the flood-related increase in vehicle-kilometres applies to sections of municipal and district roads. These are also small vehicle volumes, so the absolute deviations for different road categories are also negligible when compared to most other areas for which simulations were conducted.

7.1.4. Main rivers

As explained in Chapter 6, conducting analyses of changes in road network load that take into account floods on the main rivers in Poland makes it possible to assess how a configuration of flood hazard areas other than the approach based on water regions will affect the results of modelled travel behaviour of road network users commuting to work or making a business trip (discussed later in the chapter).

For the Vistula (Figure 7.12), the scenario of a complete breach of stopbanks deserves attention. In this variant, besides increases in vehicle numbers on road sections that drivers would use to bypass inundated areas, decreases in the volume of traffic flows become clearly visible resulting from a reduction in traffic-generating potentials. This applies primarily to Warsaw, Kraków, and Gdańsk, where a very high potential for traffic attraction coincides with a high percentage of the population at risk in this scenario. The drops observed are not restricted to the road network in the immediate vicinity but stretch over a relatively large area (including places distant from the direct impact of the flood), however, affecting low vehicle volumes.

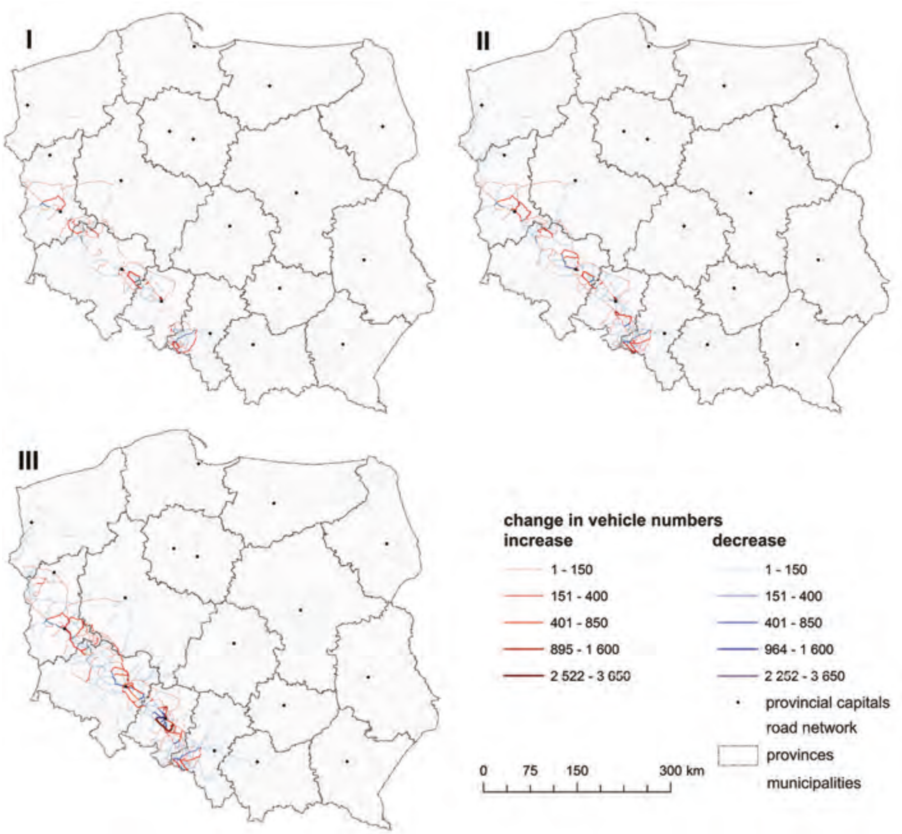
This large differentiation in changes in road network load between simulated flood scenarios was not observed for the Oder and the Warta (Figures 7.13 and 7.14). The reason for this is the clearly smaller size of areas exposed to flooding due to a complete breach of stopbanks there. Importantly, the observed increases and decreases in vehicle numbers on individual sections of the road network take on significantly lower values on average than for those simulations based on the division into water regions.



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 7.12. Changes in road network load for commuting to work due to a flood in a given scenario on the Vistula in Poland in 2019

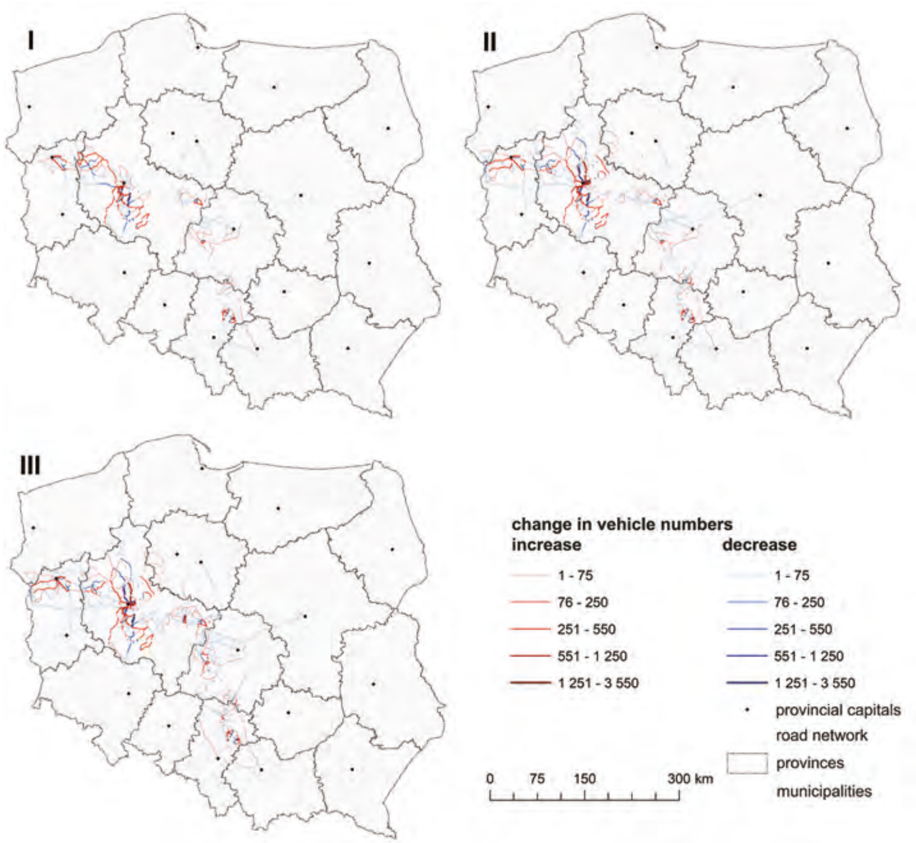
Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 7.13. Changes in road network load for commuting to work due to a flood in a given scenario on the Oder in Poland in 2019

Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 7.14. Changes in road network load for commuting to work due to a flood in a given scenario on the Warta in Poland in 2019

Source: own elaboration

A drop in the number of commuter trips – clearly visible on the road network and resulting from a complete breach of stopbanks along the Vistula – is also observed when comparing flood-related changes in the number of vehicle-kilometres (Figure 7.15). In this scenario, a significantly larger (compared to the other two variants) increment in vehicle-kilometres is accompanied by a similarly large number of vehicle-kilometres, but its magnitude here is affected by a drop in the volume of traffic flows. Analysis of the maps indicates that this number is impacted more by the cumulative length of the affected network than by the drop in vehicles observed thereon.

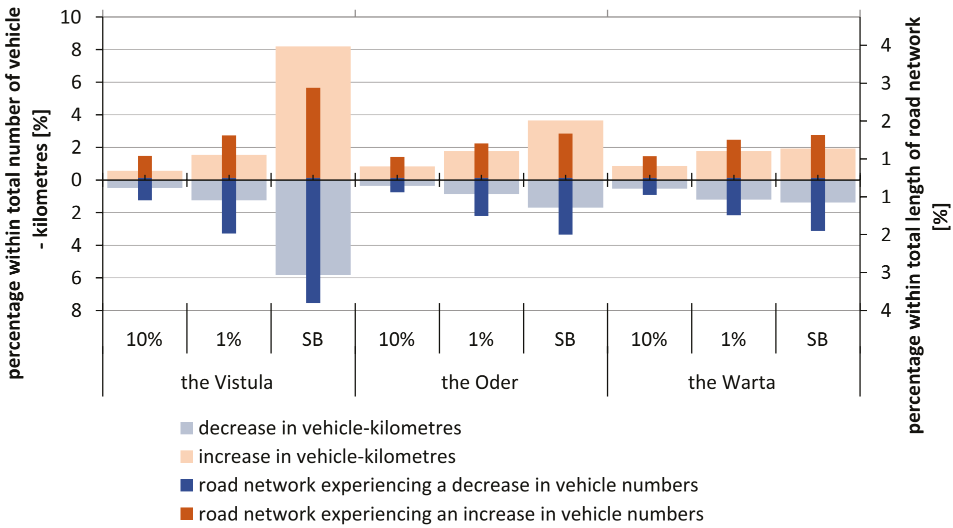


Figure 7.15. Relative changes in the number of vehicle-kilometres for commuting to work following a flood in a given scenario on main rivers in Poland in 2019

Source: own elaboration

No particular differences are revealed when the criterion of road category is applied for network sections affected by changes in the load caused by commuter traffic compared to the observations made using the approach based on water regions (Table 7.3). The greatest fluctuations in vehicle numbers are observed on regional roads, which stems from their relatively high susceptibility to the negative impact of flooding, the high density of their network, and their noticeably better (versus local roads) parameters regarding travel speed and capacity.

Table 7.3. Structure of changes in the number of vehicle-kilometres (by road category) for commuting due to a flood in a given scenario on main rivers in Poland in 2019

River	Flood scenario	Change	Road category						
			motorway (%)	express-way (%)	national (%)	regional (%)	district (%)	municipal (%)	other (%)
1	2	3	4	5	6	7	8	9	10
the Warta	SB	increase	6.4	7.3	22.2	27.8	28.9	6.6	0.7
		decrease	5.2	1.2	28.2	45.2	16.5	3.0	0.7
	1%	increase	6.5	8.1	21.5	29.0	28.2	6.1	0.6
		decrease	4.1	0.3	24.5	49.7	17.5	3.1	0.9
	10%	increase	9.0	10.7	18.5	29.7	22.5	8.2	1.3
		decrease	5.3	0.8	10.8	57.6	19.9	4.3	1.2

Table 7.3 (cont.)

1	2	3	4	5	6	7	8	9	10
the Oder	SB	increase	25.1	17.0	11.2	18.3	25.4	2.1	0.9
		decrease	4.4	1.0	45.5	38.3	8.2	1.6	0.8
	1%	increase	11.1	12.0	21.5	27.8	25.5	1.5	0.5
		decrease	6.8	2.2	33.6	43.0	10.5	2.5	1.4
	10%	increase	14.3	10.1	26.8	23.6	23.2	1.3	0.7
		decrease	6.2	2.2	25.5	51.1	9.2	3.7	2.0
the Vistula	SB	increase	6.9	13.0	38.2	25.9	13.2	2.7	0.2
		decrease	6.5	12.0	46.8	23.3	8.5	2.8	0.2
	1%	increase	4.4	7.9	34.5	39.6	11.4	2.0	0.2
		decrease	6.1	6.8	49.5	28.1	6.4	2.3	0.8
	10%	increase	4.9	4.7	32.9	45.5	9.4	2.2	0.3
		decrease	5.7	4.8	49.8	29.4	7.9	1.3	1.1

Source: own elaboration.

Simulations of a flood on the Oder confirmed the critical role of motorways and expressways for vehicle traffic when network users are forced to bypass the closed sections of roads of lower categories.

7.2. Business trips

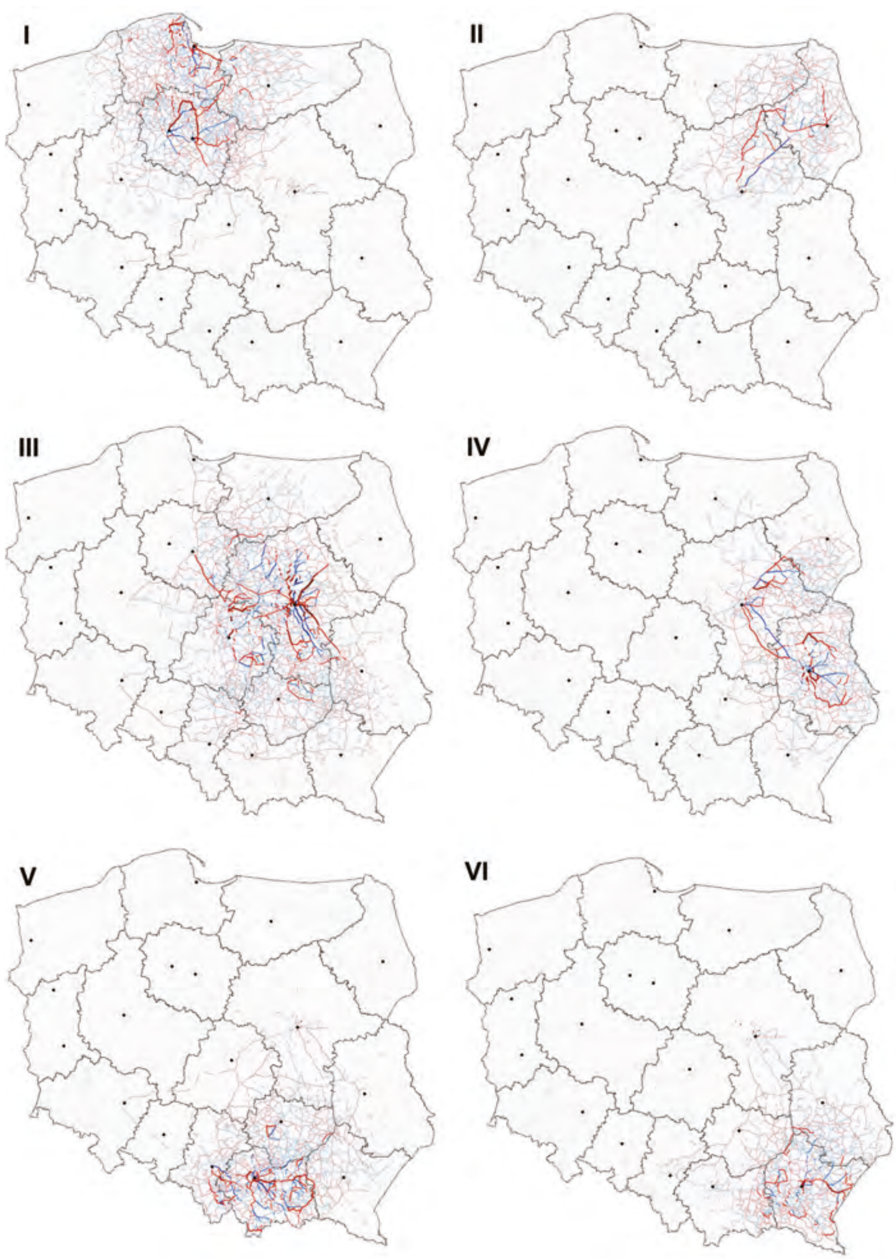
The majority of the universal properties of flood-related changes in road network load for business trips can be explained by the particular attributes of these journeys and the modelled data which enabled the construction of the traffic structure for this motivation. Since business trips are long journeys characterised by relatively low distance decay, in the model-based approach (which for business trips adopts equal potentials for traffic generation and attraction for transport regions evenly distributed in space with uniform road infrastructure), this low distance decay results in a larger spatial range of destinations for each trip origin when compared to commuting to work. This is further accentuated by the fact that there is no official data on the actual business trips made, and thus the researcher must rely on gravity models, hence the pronounced differences when compared with the results of the simulations for (significantly shorter) trips to work which were based on official matrix data on real journeys taken, thanks to which it is possible to eliminate trips that gravity models would still generate, even though they do not happen in reality.

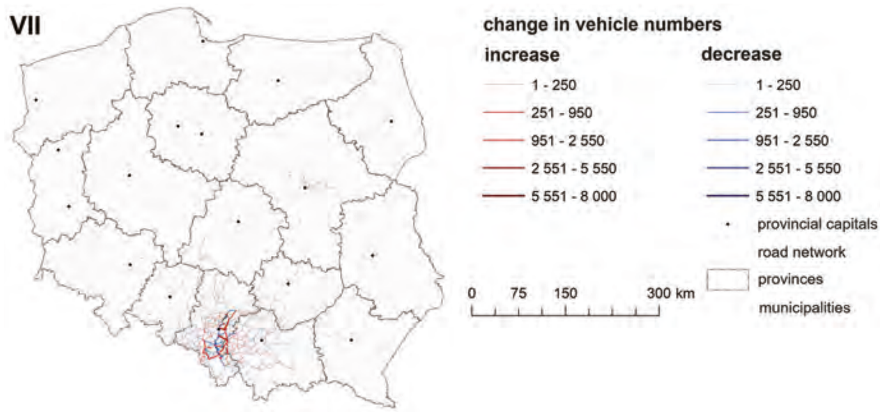
For business trips, there are also even more pronounced disparities in the distribution of traffic generation and attraction potentials than for commuting. The vast majority of the origins and destinations of business trips are concentrated in just a few locations across the country, which is particularly disadvantageous when there is an incident (here: a flood). This is because a disturbance affecting any of the key elements of the transport system can "radiate" to areas outside the direct impact of the flood. When studying changes in road network load, a manifestation of this effect may be, inter alia, symbolic drops in vehicle numbers within the road network in a region distant from the flood-affected trip destination.

On the other hand, the often long distance to a business-trip destination which has not lost its "attractiveness" following a flood but has become difficult to reach due to inundation, still allows a greater number of reasonable route choices to be selected, primarily on account of possible time gains during long journeys on motorways and expressways. When analysing the flood-related changes in road network load for business trips presented in this chapter, one must be aware of the unification of the total volumes of potential weights for the two motivations under study that was performed at the stage of trip generation, and of the correlation between these trip motivations as regards, for instance, the structure of the annual passenger car mileage.

7.2.1. The Vistula River basin

Analyses of the spatial scope of changes in traffic flow volumes observed during the simulation of a fluvial flood for the different water regions in the basin of the Vistula (Figures 7.16–7.18) most often indicate the emergence of a "core" area, where changes clearly involve large vehicle numbers but confined to a relatively small area, and a "background" area where changes in values range from a handful to several dozen vehicles but are observed within a part of the road network that covers a much larger area. Another typical feature are minor changes in vehicle numbers in the vicinity of key transport regions for business trips (mainly Warsaw) even when the flood simulation is conducted for a water region other than the Middle Vistula. When closed sections of the network are taken into account in the simulation of a 1% probability flood, this results in an increase in the length of sections where traffic flows consist of a higher number of vehicles compared to the scenario of a 10% probability flood, whereas for the scenario with a complete breach of stopbanks the drops in the length of the road network subject to traffic changes are more pronounced, especially in the previously mentioned "background" area.

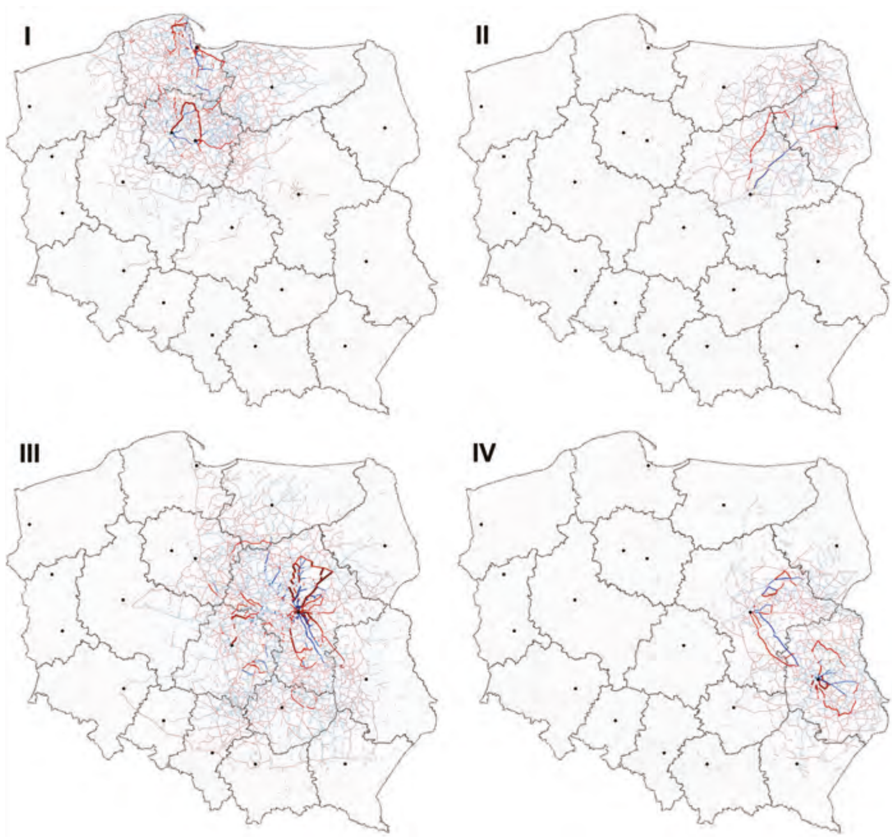

I
II
III
IV
V
VI

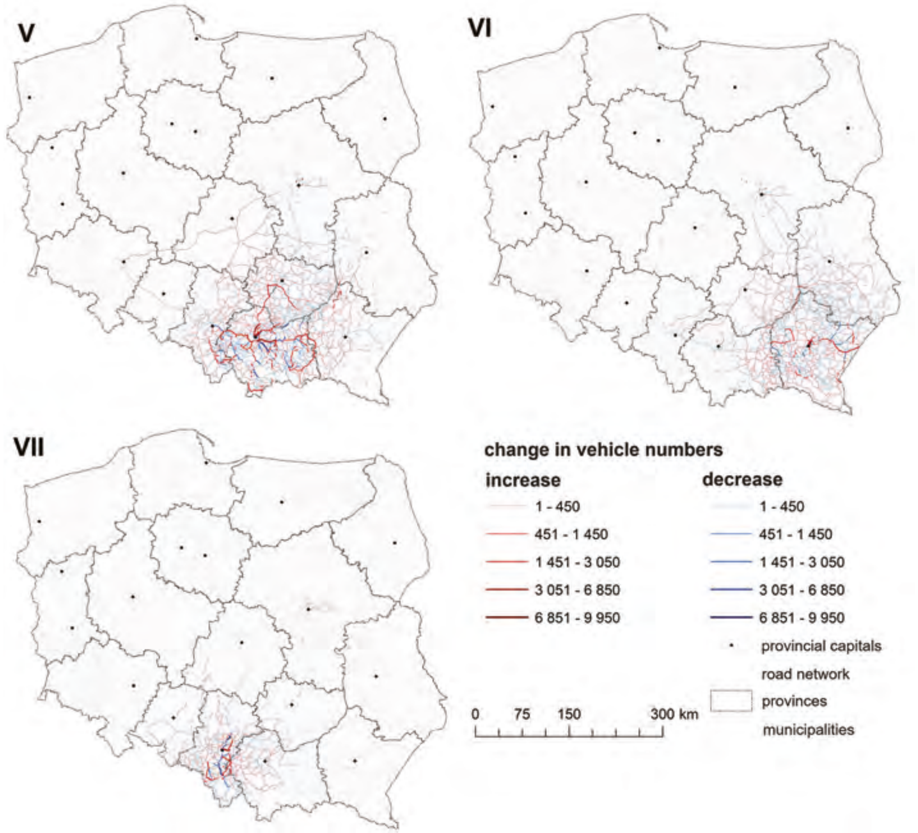


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 7.16. Changes in road network load for business trips due to a flood with a 10% probability of occurrence within the Vistula basin by water region in Poland in 2019

Source: own elaboration

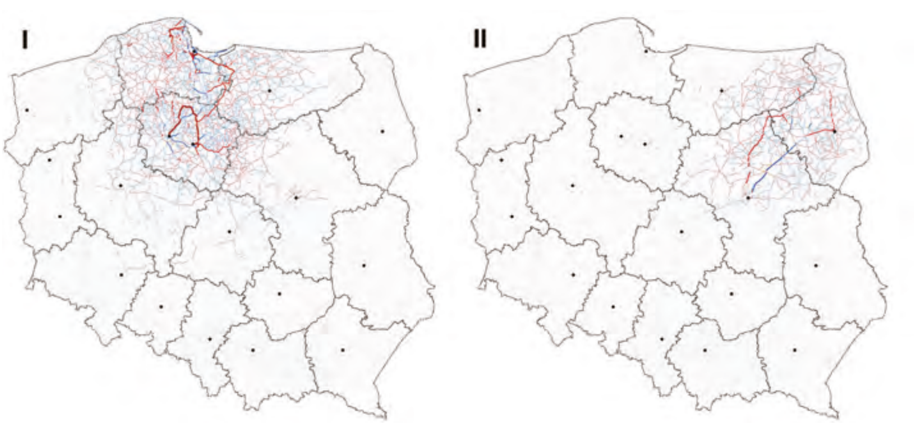


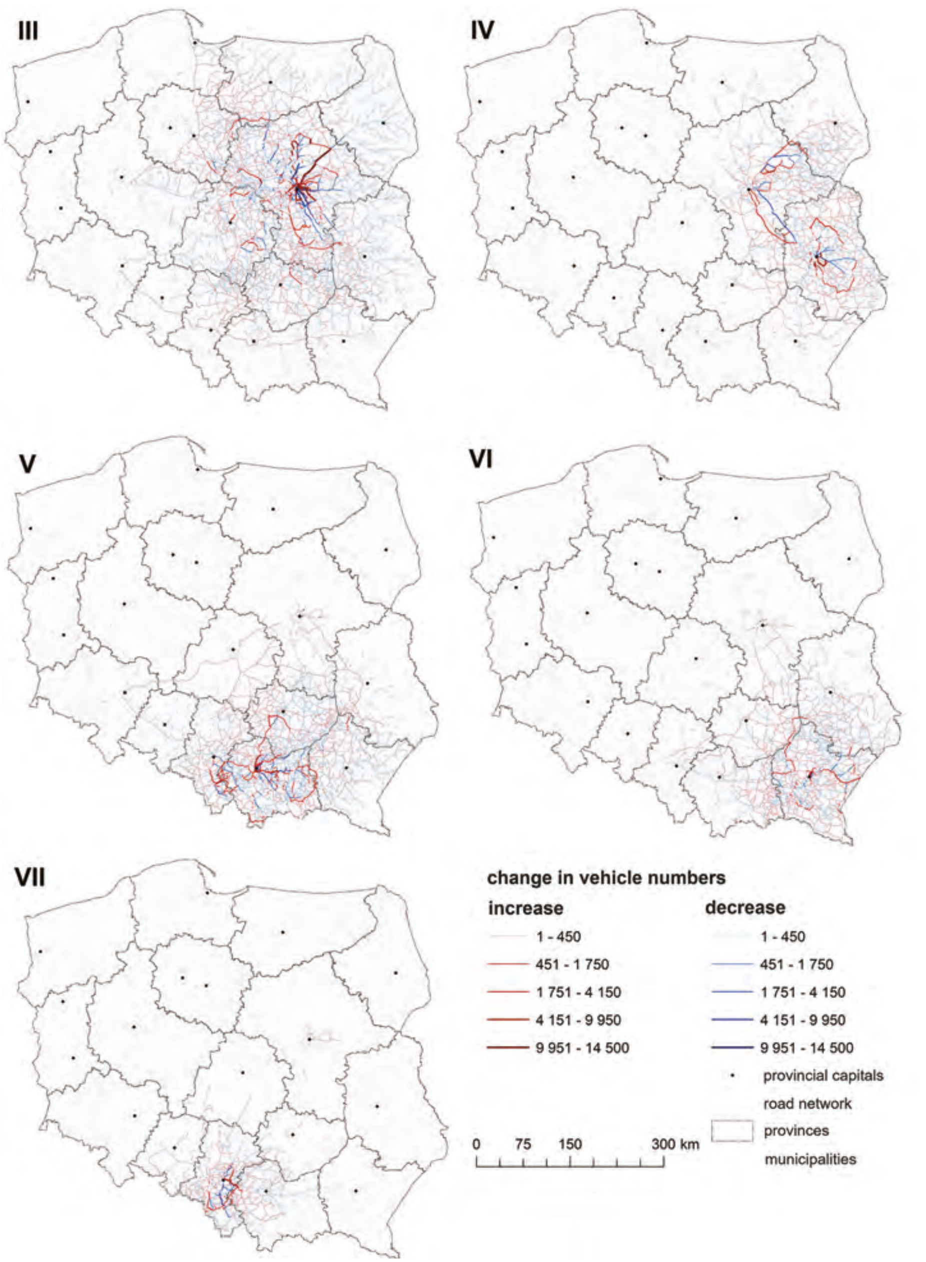


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 7.17. Changes in road network load for business trips due to a (fluvial) flood with a 1% probability of occurrence within the Vistula basin by water region in Poland in 2019

Source: own elaboration



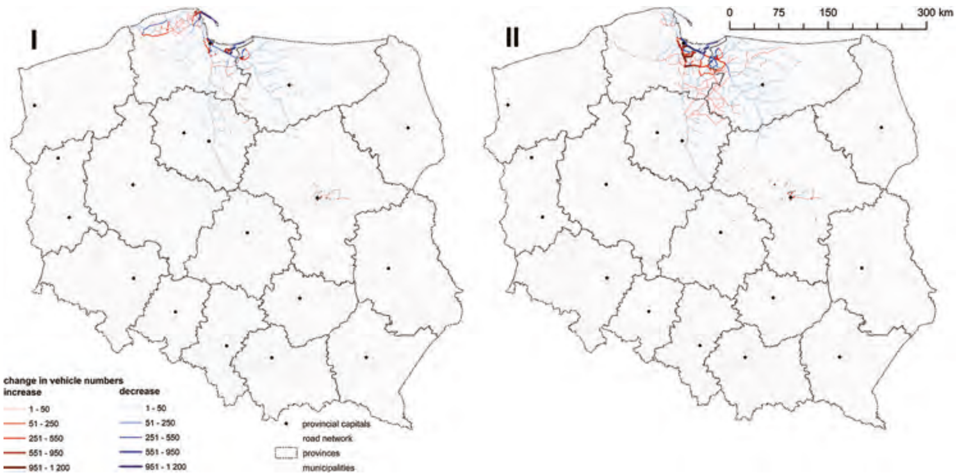


I – the Lower Vistula, II – the Narew, III – the Middle Vistula, IV – the Bug,
V – the Upper Western Vistula, VI – the Upper Eastern Vistula, VII – the Little Vistula

Figure 7.18. Changes in road network load for business trips following a flood due to a complete breach of stopbanks within the Vistula basin by water region in Poland in 2019

Source: own elaboration

For the scenarios where there is either a coastal flood with a 1% probability of occurrence or a complete breach of the protective structure of the service strip (Figure 7.19), changes in road network load would occur primarily in Pomerania and Warmia-Masuria (mostly small drops in vehicle numbers due to reductions in the traffic-generating potential of the main cities within the region of Gdańsk Pomerania).



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 7.19. Changes in road network load for business trips due to a flood in a given scenario within the water region of the Lower Vistula in Poland in 2019

Source: own elaboration

Although the observed changes in vehicle numbers on the road network seem severe for the transport system, even in the most worrying scenario they do not account for more than 12% of the total volume of vehicle-kilometres related to business trips in Poland (Figure 7.20). The (previously mentioned) noticeable increase in the number of sections affected by drops in vehicle numbers due to a complete breach of stopbanks occasionally translates into marginal increments in vehicle-kilometres when compared to the scenario with a flood of a 1% probability of occurrence. For the water regions of the Middle Vistula and the Bug, however, the situation is reversed – a complete breach of stopbanks affects the traffic-generating potentials of the transport regions under simulation to such an extent that the absolute increase in vehicle-kilometres here is lower than in the scenario of a 100-year flood. In addition, the consequences for passenger traffic for business trips are clearly concentrated in one region when compared to commuting to work.

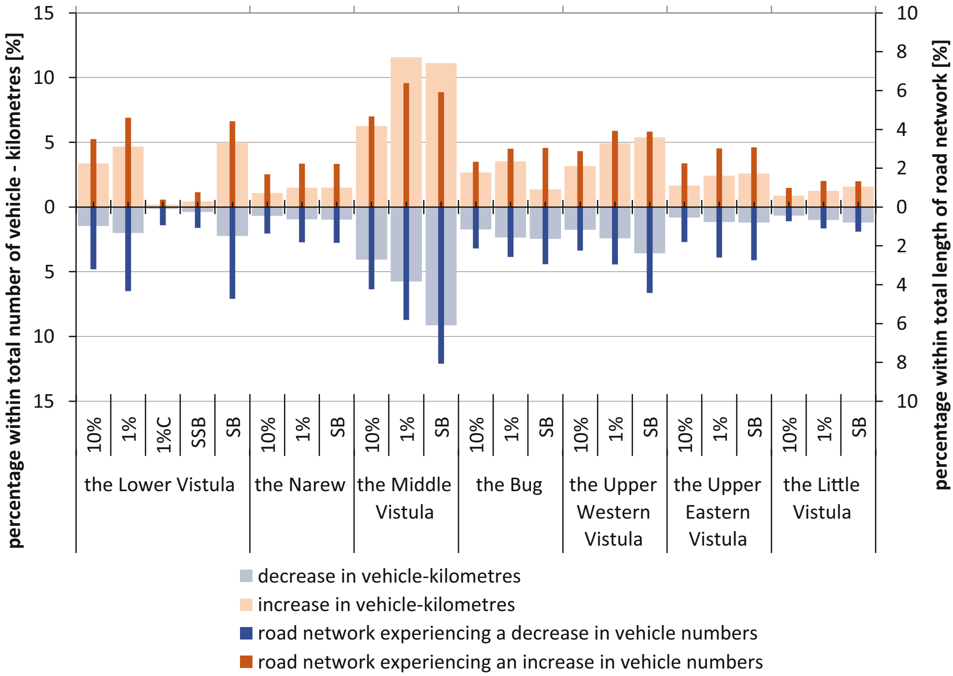


Figure 7.20. Relative changes in the number of vehicle-kilometres for business trips following a flood in a given scenario within the Vistula basin by water region in Poland in 2019

Source: own elaboration

For business trips, nearly 60% of the observed changes in traffic flow volumes accompanying floods in the Vistula basin in all analysed scenarios were observed on sections of national and regional roads (Table 7.4), with approximately one third being recorded for motorways and expressways. A large percentage of roads of these categories serve the diverted vehicle traffic bypassing the affected areas while travelling on business. This is observed in almost all scenarios and areas of simulation.

Table 7.4. Structure of changes in the number of vehicle-kilometres (by road category) for business trips due to a flood in a given scenario in the Vistula basin by water region in Poland in 2019

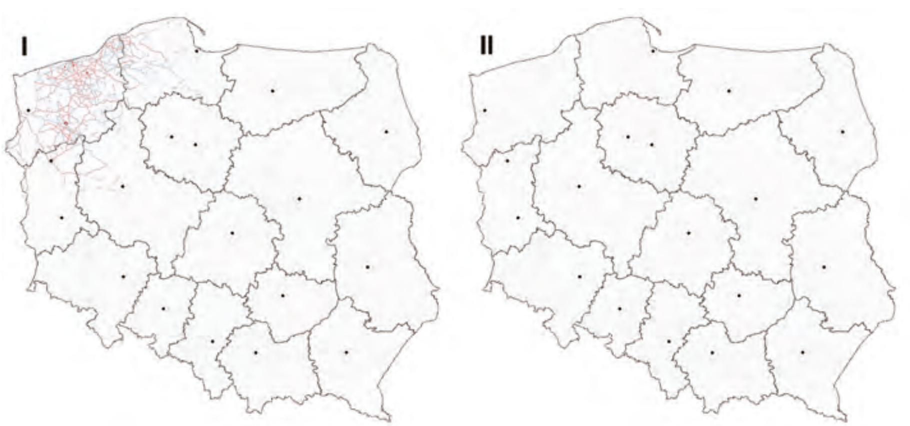
Water region	Flood scenario	Change	Road category						
			motorway (%)	express-way (%)	national (%)	regional (%)	district (%)	municipal (%)	other (%)
1	2	3	4	5	6	7	8	9	10
the Little Vistula	SB	increase	24.8	16.4	14.3	21.7	15.0	7.3	0.5
		decrease	2.6	10.6	65.6	11.9	8.3	1.0	0.1
	1%	increase	10.3	17.3	27.1	25.8	16.5	2.5	0.5
		decrease	3.4	13.7	63.0	12.5	6.7	0.7	0.1
	10%	increase	11.3	17.0	30.3	24.0	14.9	1.7	0.7
		decrease	3.6	15.2	61.2	11.9	7.3	0.8	0.1
the Upper Eastern Vistula	SB	increase	23.7	3.0	11.7	23.8	34.2	3.1	0.4
		decrease	1.6	3.4	47.6	33.0	12.9	1.2	0.2
	1%	increase	23.8	2.9	10.6	24.0	35.2	3.0	0.5
		decrease	1.8	3.5	46.1	33.8	13.2	1.2	0.2
	10%	increase	25.2	1.6	10.3	24.7	34.7	3.1	0.4
		decrease	1.1	4.4	45.4	34.1	13.5	1.3	0.2
the Upper Western Vistula	SB	increase	18.0	3.7	25.2	22.4	25.1	5.0	0.5
		decrease	8.0	5.4	35.3	32.8	14.9	3.4	0.2
	1%	increase	20.7	4.5	23.1	22.7	23.0	5.5	0.5
		decrease	4.1	4.2	35.4	37.8	14.4	3.9	0.2
	10%	increase	22.8	5.3	24.4	18.7	23.4	4.9	0.5
		decrease	5.0	4.6	37.5	34.4	13.9	4.4	0.2
the Bug	SB	increase	0.2	9.1	27.8	40.7	20.8	1.3	0.1
		decrease	0.2	18.9	46.9	23.0	9.8	1.1	0.1
	1%	increase	0.3	7.8	28.1	44.4	18.2	1.1	0.1
		decrease	0.0	19.8	47.0	22.7	9.4	1.1	0.1
	10%	increase	0.1	9.2	29.2	40.6	19.9	0.9	0.1
		decrease	0.2	16.7	48.3	23.8	9.8	1.2	0.1
the Middle Vistula	SB	increase	2.3	37.1	19.7	14.3	23.2	3.3	0.1
		decrease	2.1	3.1	44.8	36.8	11.7	1.4	0.0
	1%	increase	2.6	24.6	25.1	20.6	23.1	3.9	0.1
		decrease	0.7	7.2	44.6	34.4	11.6	1.4	0.0
	10%	increase	6.9	21.6	32.1	16.6	17.0	5.6	0.2
		decrease	0.8	6.1	41.2	37.8	12.8	1.3	0.0
the Narew	SB	increase	0.2	9.3	38.4	31.5	16.7	3.2	0.6
		decrease	0.4	62.0	18.3	12.5	7.8	1.9	0.1
	1%	increase	0.2	9.5	37.9	31.6	17.0	3.2	0.6
		decrease	0.4	59.4	18.1	12.3	7.7	1.9	0.1
	10%	increase	0.2	9.8	37.3	31.1	17.6	3.3	0.7
		decrease	0.4	58.0	18.7	12.7	7.9	2.0	0.2

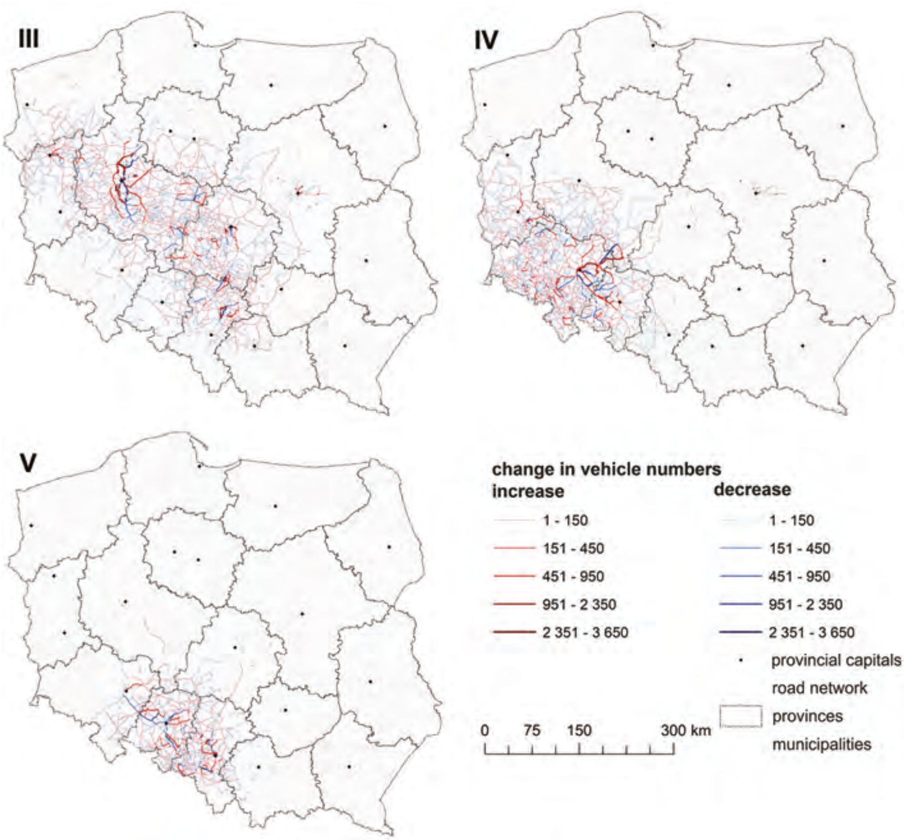
1	2	3	4	5	6	7	8	9	10
the Lower Vistula	SB	increase	14.7	16.6	15.8	15.1	29.4	8.2	0.1
		decrease	4.2	4.2	45.1	28.4	12.8	4.6	0.7
	SSB	increase	14.8	24.6	24.4	6.7	25.8	3.6	0.1
		decrease	1.5	32.7	17.3	23.8	16.6	5.2	2.7
	1%C	increase	2.3	18.4	20.5	7.8	25.9	25.1	0.0
		decrease	2.3	15.0	7.4	57.7	12.5	1.8	3.4
	1%	increase	16.2	10.6	19.6	14.4	30.9	8.0	0.2
		decrease	4.5	4.9	46.0	28.5	11.7	4.2	0.1
	10%	increase	15.6	11.3	19.2	14.8	30.7	8.3	0.1
		decrease	4.5	4.9	46.0	28.2	11.9	4.3	0.1

Source: own elaboration.

7.2.2. The Oder River basin

In the basin of the Oder, the spatial scope of the road network affected by changes in vehicle numbers is comparable to the results observed in the simulations for the basin of the Vistula, but the volume of vehicles involved is substantially smaller (Figures 7.21–7.23). Due to the scope of the flood simulations and the presence of major traffic attractors in the basin of the Oder (the cities of Poznań, Wrocław, and Zielona Góra), the road networks within the water regions of the Warta and the Middle Oder would have to cope with serious threats to transport equilibrium. In the water region of the Noteć, however, only a complete breach of stopbanks would cause a significant disturbance to passenger car transport (which is concordant with the results of the simulations conducted for commuting to work).

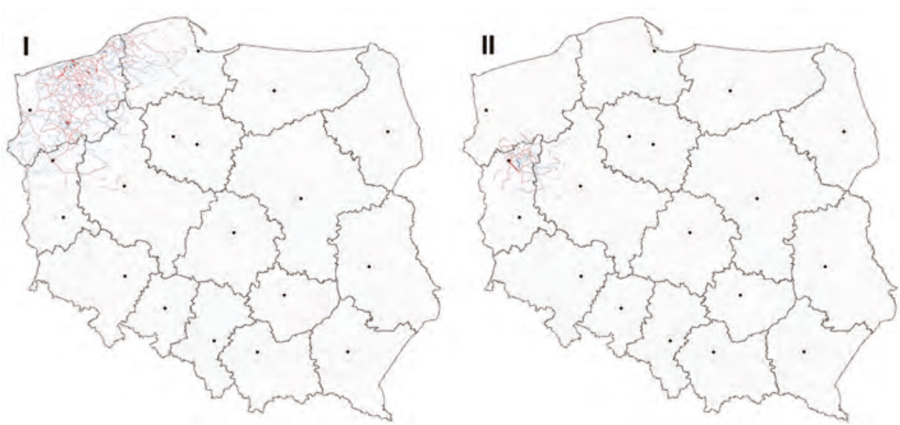


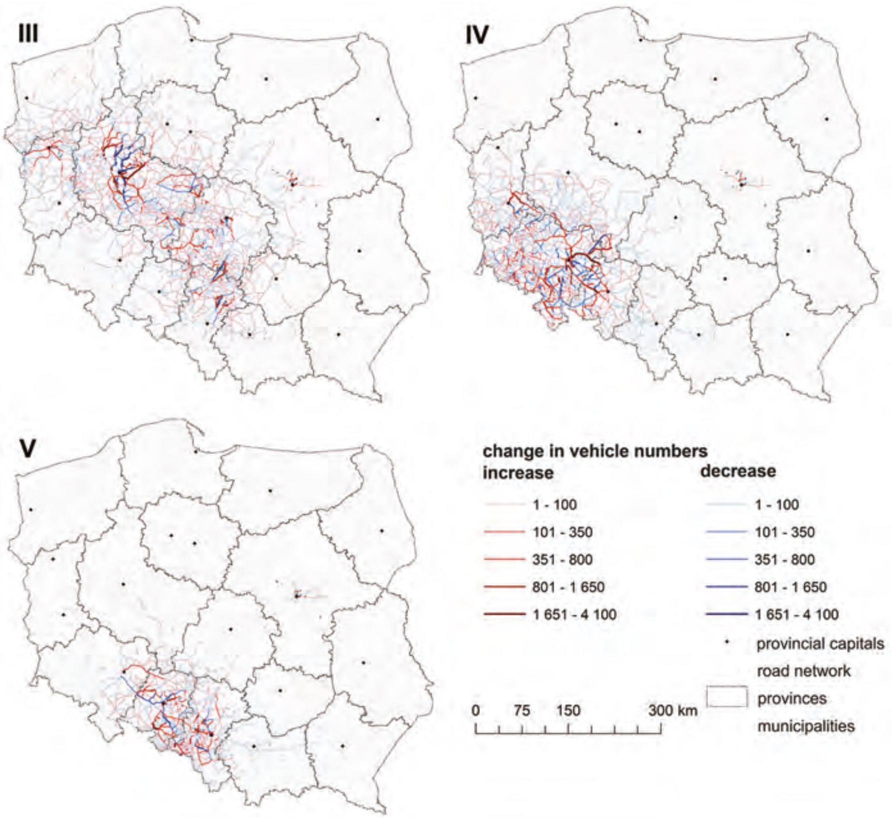


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć,
III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 7.21. Changes in road network load for business trips due to a flood with a 10% probability of occurrence within the Oder basin by water region in Poland in 2019

Source: own elaboration

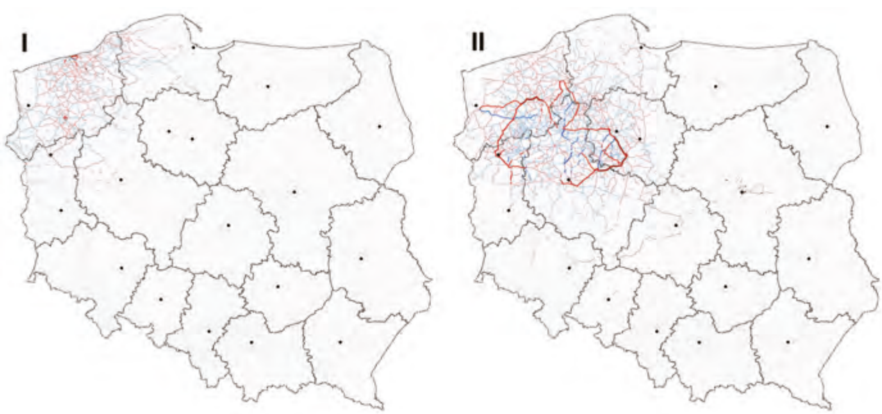


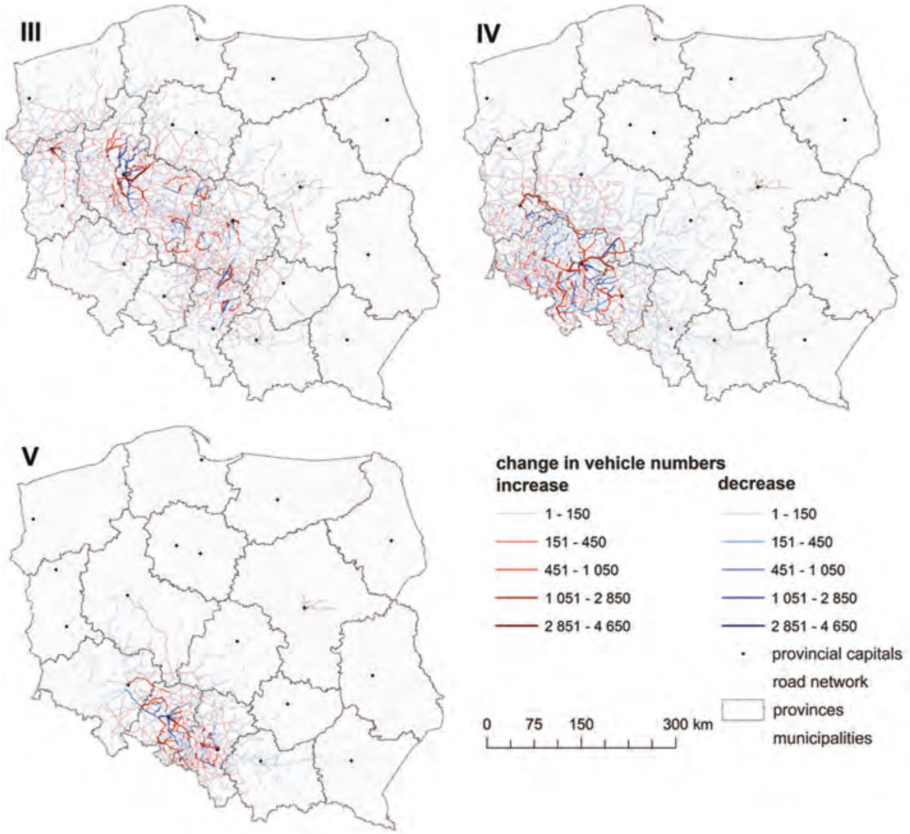


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć,
III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 7.22. Changes in road network load for business trips due to a (fluvial) flood with a 1% probability of occurrence within the Oder basin by water region in Poland in 2019

Source: own elaboration



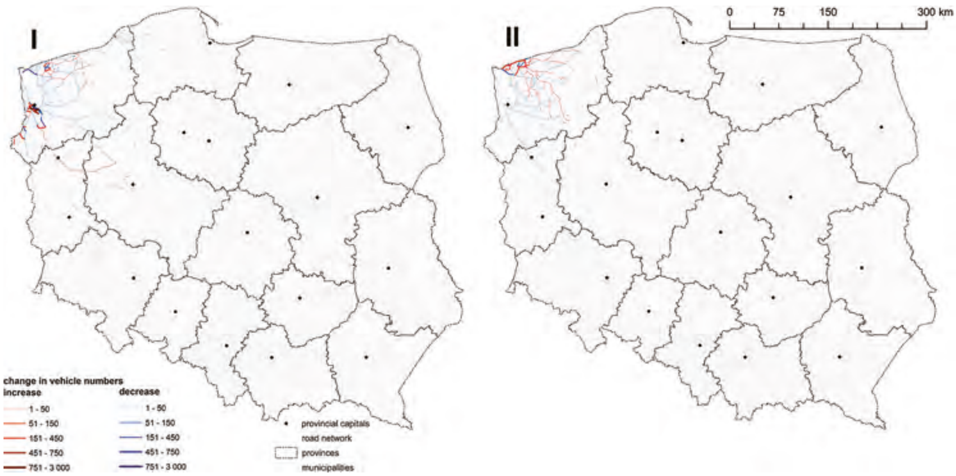


I – the Lower Oder and the coastal strip of West Pomerania, II – the Noteć, III – the Warta, IV – the Middle Oder, V – the Upper Oder

Figure 7.23. Changes in road network load for business trips following a flood due to a complete breach of stopbanks within the Oder basin by water region in Poland in 2019

Source: own elaboration

A coastal event (similarly to a fluvial flood) would not pose a major challenge to the transport network within the north-western provinces of Poland (Figure 7.24). As regards business trips there, the changes in road network load are observed almost exclusively in West Pomerania. Intensified disruptions to traffic distribution, which may pose a threat to the equilibrium of the transport system, are only found in the immediate vicinity of Szczecin, Koszalin, and Kołobrzeg.



I – 1% probability (coastal flooding), II – a complete breach of the protective structure of the service strip

Figure 7.24. Changes in road network load for business trips due to a flood in a given scenario within the water region of the Lower Oder and the coastal strip of West Pomerania in Poland in 2019

Source: own elaboration

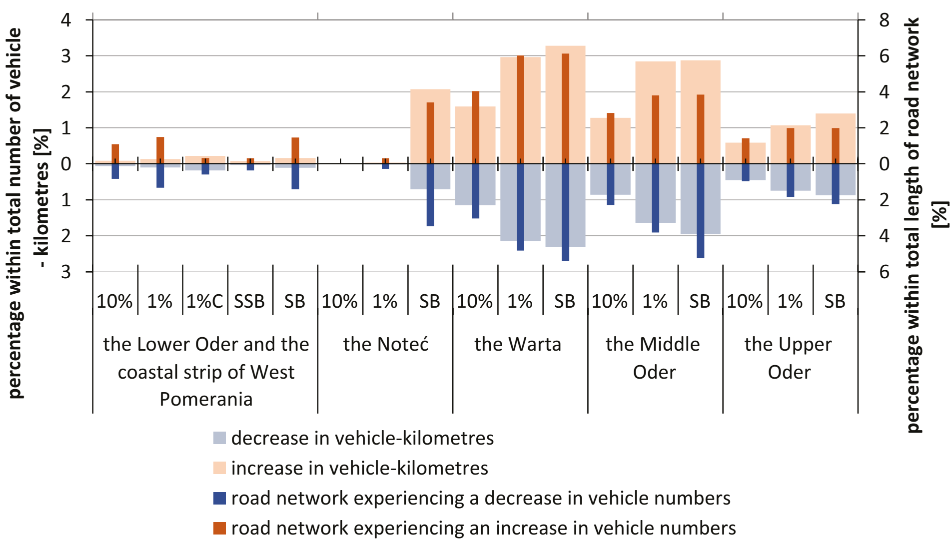


Figure 7.25. Relative changes in the number of vehicle-kilometres for business trips following a flood in a given scenario within the Oder basin by water region in Poland in 2019

Source: own elaboration

Among the five water regions covered by flood simulations, business trips could still be successfully accomplished within the Lower Oder and the coastal strip of West Pomerania, the Noteć, and the Upper Oder (Figure 7.25). For the two remaining water regions, the costs (e.g., expressed in time units) associated with business trips taken when there is a flood may increase significantly.

When compared to the changes in the number of vehicle-kilometres by road category observed for the basin of the Vistula, the importance of national and regional roads within the basin of the Oder hardly changes (Table 7.5). However, the percentage of roads of the highest parameters drops by over 50%. For the basin of the Oder, certain sections of the local road infrastructure are very important, especially for road network users forced to find a new route (approximately 25% of the noted absolute changes in vehicle numbers are observed on roads of these categories).

Table 7.5. Structure of changes in the number of vehicle-kilometres (by road category) for business trips due to a flood in a given scenario in the Oder basin by water region in Poland in 2019

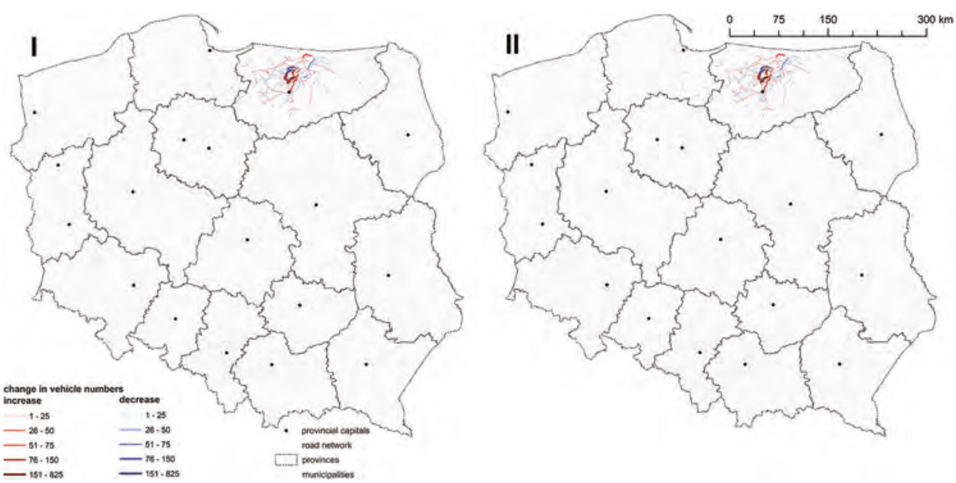
Water region	**Flood scenario**	**Change**	**Road category**						
			motorway (%)	**express-way (%)**	**national (%)**	**regional (%)**	**district (%)**	**municipal (%)**	**other (%)**
1	2	3	4	5	6	7	8	9	10
the Upper Oder	SB	increase	10.9	3.2	31.0	24.4	28.3	1.6	0.6
		decrease	16.6	0.4	45.0	26.5	11.0	0.4	0.1
	1%	increase	11.9	4.7	28.8	24.7	27.4	1.8	0.7
		decrease	16.9	0.4	41.2	29.8	11.0	0.5	0.1
	10%	increase	13.7	5.0	33.0	24.1	21.8	1.8	0.6
		decrease	17.4	0.3	37.6	32.6	11.3	0.6	0.3
the Middle Oder	SB	increase	13.2	17.0	12.8	30.4	21.2	4.6	0.7
		decrease	3.7	5.3	38.3	29.9	18.3	4.0	0.5
	1%	increase	12.3	20.4	12.9	31.5	18.9	3.1	0.8
		decrease	1.1	3.7	40.5	30.6	19.4	4.1	0.6
	10%	increase	11.6	21.3	16.8	22.2	21.0	6.1	0.9
		decrease	6.9	1.6	38.3	29.6	19.3	3.9	0.4
the Warta	SB	increase	7.4	19.8	20.2	20.7	25.4	5.6	0.8
		decrease	2.9	4.6	37.1	38.3	12.9	3.9	0.4
	1%	increase	6.8	17.7	21.9	21.5	25.8	5.5	0.7
		decrease	3.0	4.9	35.2	39.8	12.7	4.0	0.4
	10%	increase	4.8	9.9	22.8	28.7	23.9	8.0	1.9
		decrease	4.2	5.4	26.0	45.0	15.6	3.6	0.2
the Noteć	SB	increase	3.4	15.1	35.8	21.5	12.7	10.4	1.1
		decrease	0.7	3.9	48.4	27.2	10.7	7.9	1.3
	1%	increase	0.7	24.6	21.8	18.6	13.0	19.3	1.9
		decrease	0.6	0.9	0.3	49.3	13.2	24.7	11.0
	10%	increase	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		decrease	6.7	1.2	40.8	40.9	3.1	7.3	0.0

1	2	3	4	5	6	7	8	9	10
the Lower Oder and the coastal strip of West Pomerania	SB	increase	0.8	1.3	22.6	23.2	32.1	18.4	1.6
		decrease	0.3	2.2	17.7	50.5	16.2	11.6	1.6
	SSB	increase	0.0	0.6	0.8	77.7	15.6	4.8	0.6
		decrease	0.2	6.5	46.0	33.6	5.2	8.5	0.1
	1%C	increase	27.9	1.7	41.0	7.3	13.2	8.8	0.0
		decrease	0.1	1.9	67.7	21.4	5.1	3.6	0.1
	1%	increase	1.0	1.7	15.4	32.0	27.7	20.3	1.9
		decrease	0.2	2.4	18.5	48.9	16.8	11.6	1.7
	10%	increase	1.2	2.2	11.6	34.6	26.3	21.8	2.3
		decrease	0.1	2.6	21.6	47.0	15.7	10.9	2.0

Source: own elaboration.

7.2.3. The Pregolya River basin

When business trips are taken into account in the simulations for the water region of the Łyna and the Węgorapa, this motivation does not fundamentally change the impact that a flood would have on the passenger road transport there. Irrespective of the adopted flood probability, its possible effects on changes in road network load remain very small regarding both the number of vehicles affected and the area over which these changes would occur (Figure 7.26). Even though business travel is characterised by a lower distance decay than commuting to work, the observed changes are still confined within the borders of Warmian-Masurian Province.



I – 10% probability, II – 1% probability

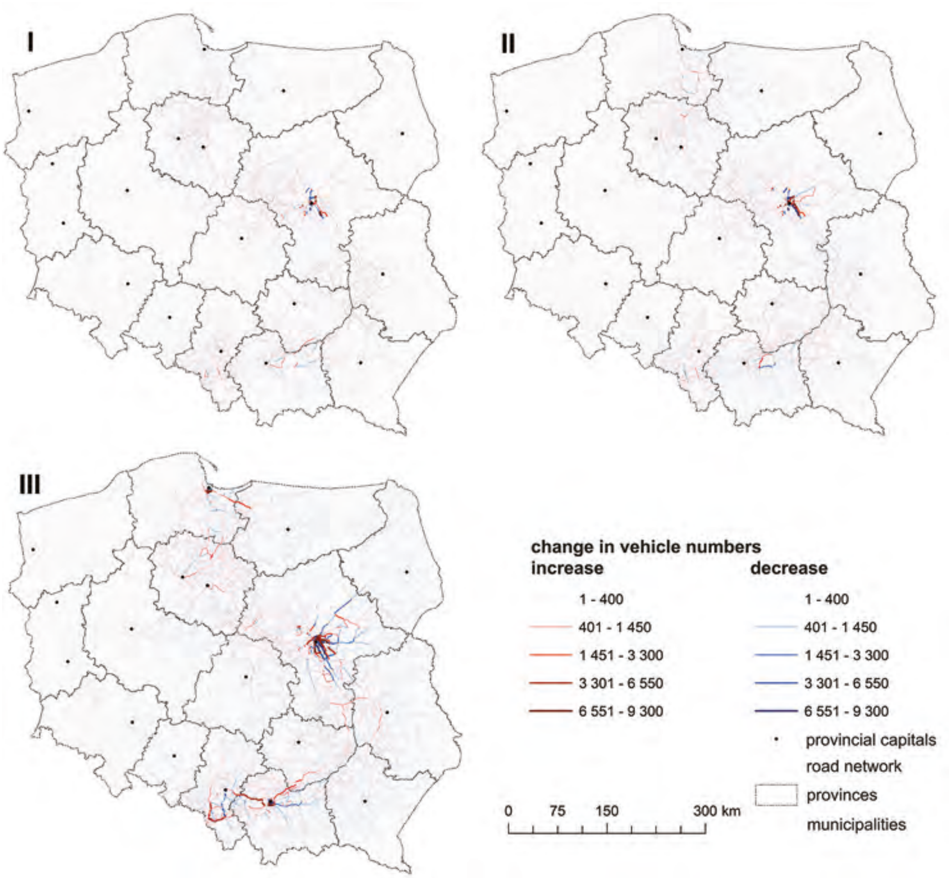
Figure 7.26. Changes in road network load for business trips due to a flood in a given scenario within the water region of the Łyna and the Węgorapa in Poland in 2019

Source: own elaboration

The localised nature of the flood-related changes to the road network in the basin of the Pregolya is manifested by a rise in the number of vehicle-kilometres for both the 10% and 1% probability, but this increase remains below 0.06% of the total volume of vehicle-kilometres for business trips in Poland. When the analysis focuses on the categories of roads affected by changes in vehicle numbers, there are significant differences compared to simulations for short trips (commuting to work). For business trips, the changes are mainly observed on national roads, although regional and municipal roads are also important. As opposed to the simulation results presented above, a flood in the water region of the Łyna and the Węgorapa "relocates" vehicle traffic onto roads of lower categories. What remains unchanged, however, is the very low vehicle volume, when its increase or decrease is observed for each road category.

7.2.4. Main rivers

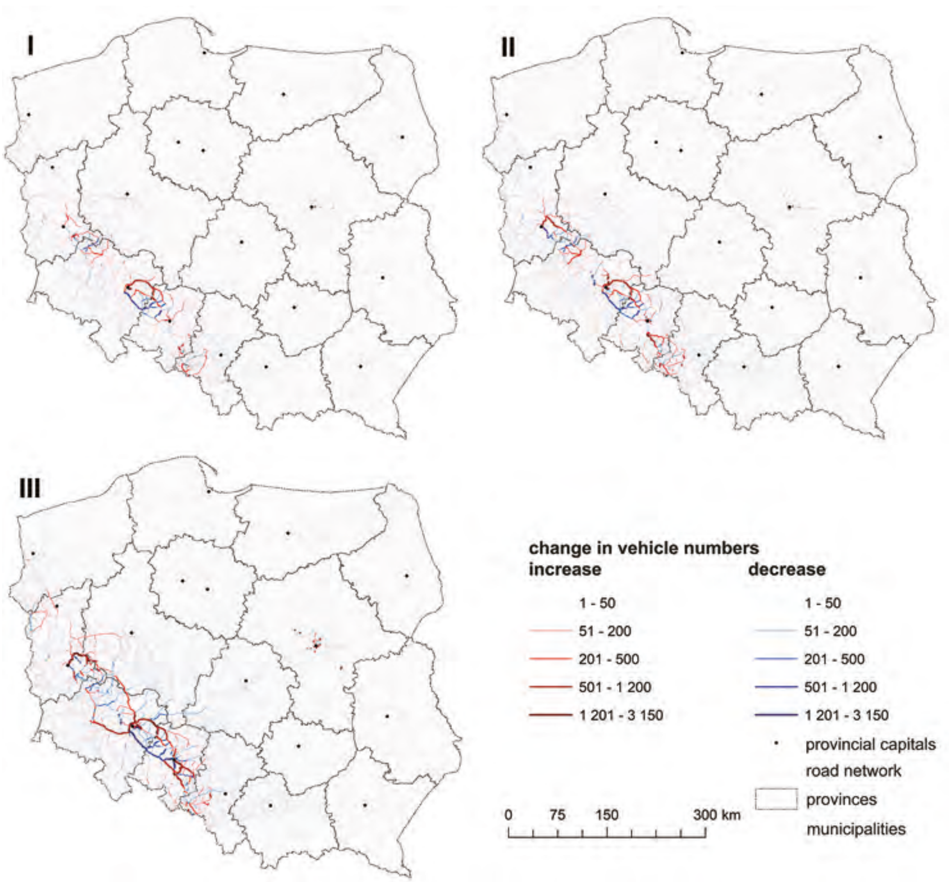
A shift in the research approach, from simulations based on water regions to those conducted for the largest rivers in Poland, generally indicates that although the occurrence of a flood impacts passenger car transport, this impact is not significant in all scenarios except for a complete breach of stopbanks along the Vistula. The flood-related changes to the road network and the resulting cancellation of some trips reach relatively high values in absolute terms, but are still significantly lower (Figures 7.27–7.29) when compared to the results of the simulations conducted for individual water regions. The results obtained (especially for floods on the Vistula) again indicate the occurrence of the previously mentioned area of concentration of pronounced changes in road network load and the larger area of only symbolic changes (mainly slight drops in traffic flow volumes). This confirms the key role of the largest cities in shaping the spatial distribution of business trips. The decline in the attractiveness of just a few transport regions can be felt in sections of the network that are several hundred kilometres away. Naturally, these changes are particularly evident for high-speed, supra-local roads (Table 7.6). The spatial scope of the changes seems very extensive, but the percentage of the network covered by them within the cumulative length of the country's road network does not indicate this (Figure 7.30).



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 7.27. Changes in road network load for business trips due to a flood in a given scenario on the Vistula in Poland in 2019

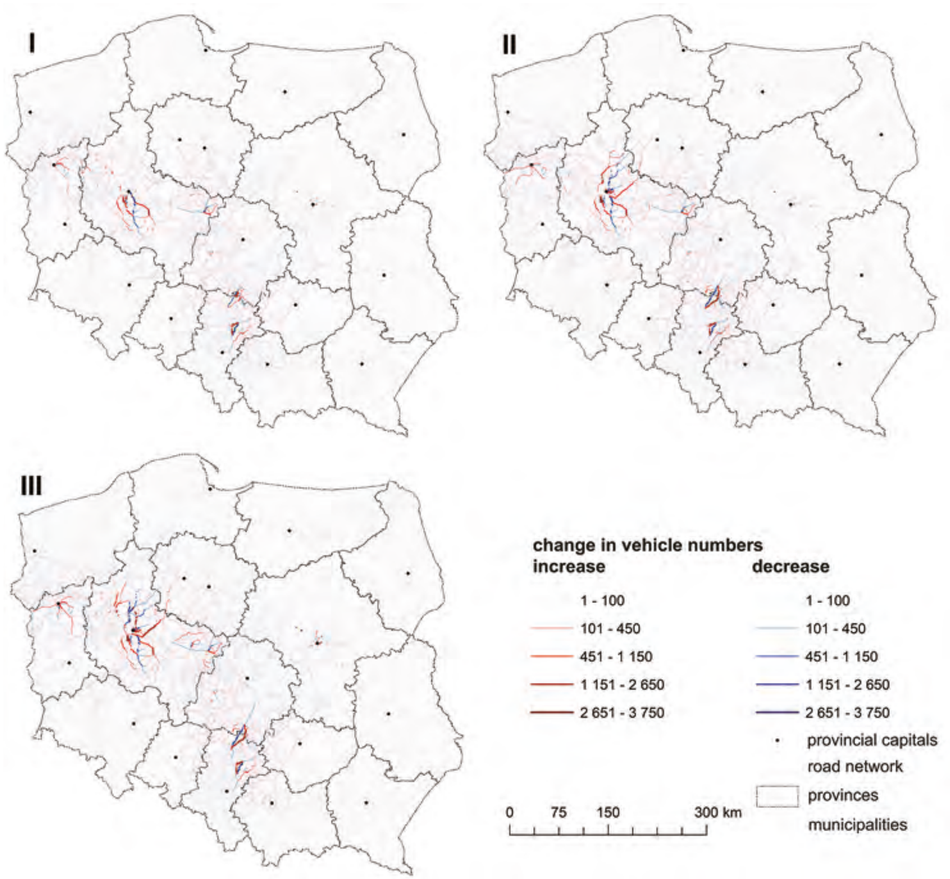
Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 7.28. Changes in road network load for business trips due to a flood in a given scenario on the Oder in Poland in 2019

Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – a complete breach of stopbanks

Figure 7.29. Changes in road network load for business trips due to a flood in a given scenario on the Warta in Poland in 2019

Source: own elaboration

In the flood simulations conducted for the main rivers, the great relevance of the decline in the number of business trips (especially in view of the limited length of the road network directly affected by flood) becomes evident through the small differences between the increases and decreases in vehicle-kilometres for different scenarios under study (Figure 7.30). When a complete breach of stopbanks along the Vistula is simulated, the drops in the number of vehicle-kilometres and the total length of the road network sections where there is an absolute decline in vehicle numbers within traffic flows exceed any increase.

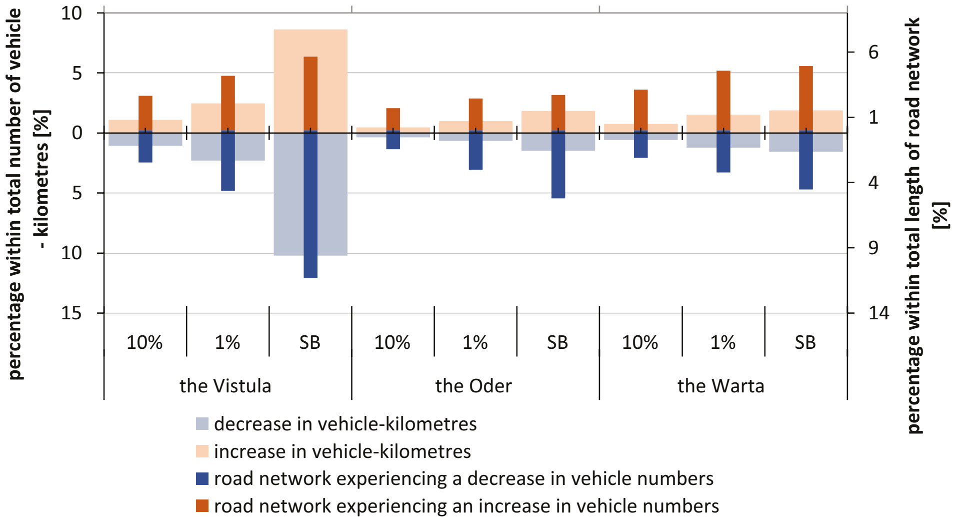


Figure 7.30. Relative changes in the number of vehicle-kilometres for business trips following a flood in a given scenario on main rivers in Poland in 2019

Source: own elaboration

The said falls in vehicle numbers on national roads, expressways, and motorways are also observed within the structure of changes in the number of vehicle-kilometres by road category (Table 7.30). In this case, one cannot speak of a regularity that appears in all scenarios, but these drops are certainly more pronounced than those observed for commuting to work or the simulations conducted for individual water regions. Disregarding the direction of changes in road network load, the percentage of (1) motorways and expressways, (2) national and regional roads, and (3) local road networks that all cope with changes in traffic volumes more or less reflects the following ratio: (1) 60% to (2) 20% to (3) 20%.

Table 7.6. Structure of changes in the number of vehicle-kilometres (by road category) for business trips due to a flood in a given scenario on main rivers in Poland in 2019

River	Flood scenario	Change	Road category						
			motorway (%)	express-way (%)	national (%)	regional (%)	district (%)	municipal (%)	other (%)
the Warta	SB	increase	4.7	12.4	27.3	21.4	28.9	4.9	0.5
		decrease	3.8	6.3	38.1	36.6	11.6	3.1	0.5
	1%	increase	3.5	11.5	35.2	18.9	26.1	4.4	0.5
		decrease	4.2	5.3	30.8	44.0	12.7	2.7	0.4
	10%	increase	2.8	5.8	29.2	24.9	29.5	7.0	0.9
		decrease	5.6	8.0	26.2	44.1	12.4	3.4	0.3
the Oder	SB	increase	16.4	17.0	21.9	24.5	16.6	2.4	1.1
		decrease	24.7	7.6	31.5	23.1	10.8	1.9	0.4
	1%	increase	10.2	19.7	18.8	32.1	16.8	1.9	0.3
		decrease	20.5	5.1	30.9	27.5	13.2	2.3	0.5
	10%	increase	11.2	16.3	17.3	35.2	15.9	3.6	0.5
		decrease	24.0	3.7	30.4	24.6	15.3	1.6	0.4
the Vistula	SB	increase	12.3	17.2	21.0	23.9	21.1	4.4	0.1
		decrease	7.5	9.7	38.8	31.4	10.4	2.0	0.2
	1%	increase	3.9	2.4	24.4	52.9	13.3	3.0	0.0
		decrease	7.9	12.9	32.4	37.5	7.9	1.3	0.0
	10%	increase	6.6	3.3	30.1	40.0	18.3	1.7	0.0
		decrease	5.5	14.4	38.5	31.3	8.7	1.5	0.1

Source: own elaboration.

8

EFFECTS OF FLOODING ON PASSENGER ROAD TRANSPORT – A SYNTHESIS

Assessment of the impact that non-typical events (regardless of origin) have on the performance of transport (irrespective of type) always poses a major challenge and, regardless of the source data involved or the sophistication of the methodological potential applied, it forces the researcher to make an assessment only within a strictly defined spectrum of the issue. As regards the impact of floods on the operation of road transport, the two extremely complex issues of transport and floods overlap (both of which are of interest to specialists in many scientific disciplines). These phenomena are subject to modelling to ensure predictability, despite their complexity, and in order to study their changeability in the face of the labile properties of the system in which they operate. Thanks to models that map the limits of flood hazard areas, the road network, the changes in travel speeds of passenger car on the network, and travel paths of those either commuting to work or on longer business trips, it is possible to analyse a large number of factors across an extensive, national spatial range. One should be aware, however, that the results obtained from model-based analyses may be burdened with typical weaknesses. For instance, the effects of floods on the road transport in this study are considered only in terms of changes in transport accessibility and road network load. The focus of this study was solely on the domestic travel and passenger car transport (with no separate analysis of the social and economic impact of flooding). The variety of flood scenarios and the applied trip lengths and motivations produced a number of different results. However, it must be stressed that even though the simulations that incorporated combinations of the two above variables are a valuable source of information, it still seems worth making general conclusions and comments.

8.1. Effects on transport accessibility

The research results presented in Chapter 6 confirm the impact of flood events on transport accessibility. This is shown both in the context of analyses based solely on the transport component (isochronous accessibility) and those including the land-use/demographic component (cumulative and potential accessibility). The returned results reveal the range of the disruptions to normal levels of accessibility and their spatial extent.

A number of previous studies have employed an approach based on measuring accessibility to assess the impact of the changes that occur in the transport system. The magnitude of the impact on accessibility has often been employed to determine what effect new or upgraded road sections have on the transport network in Poland. Rokicki and Stępniak (2018) applied the potential accessibility index for Poland to verify the overall effect of the major investments in transport infrastructure accomplished between 2004 and 2014. Similar studies were conducted, inter alia, by Rosik, Komornicki and Goliszek (2017), Rosik et al. (2013), Komornicki et al. (2010, 2015, 2017), Rosik, Stępniak and Komornicki (2015), Stępniak and Rosik (2013, 2016, 2018), Śleszyński and Kretowicz (2016), Bul (2016), Wiskulski and Taraszkiewicz (2015). This approach has also been employed for the public transport subsystem, where changes in accessibility were analysed, for instance, to assess whether the decisions taken on the location of certain infrastructure were correct (Gadziński and Beim 2009, Wolański 2010, Puławska and Starowicz 2011, Koźlak 2012, Kwarciński 2013, Goliszek 2014ab, 2016, Goliszek and Połom 2016ab, Guzik 2016, Malasek 2017, etc.).

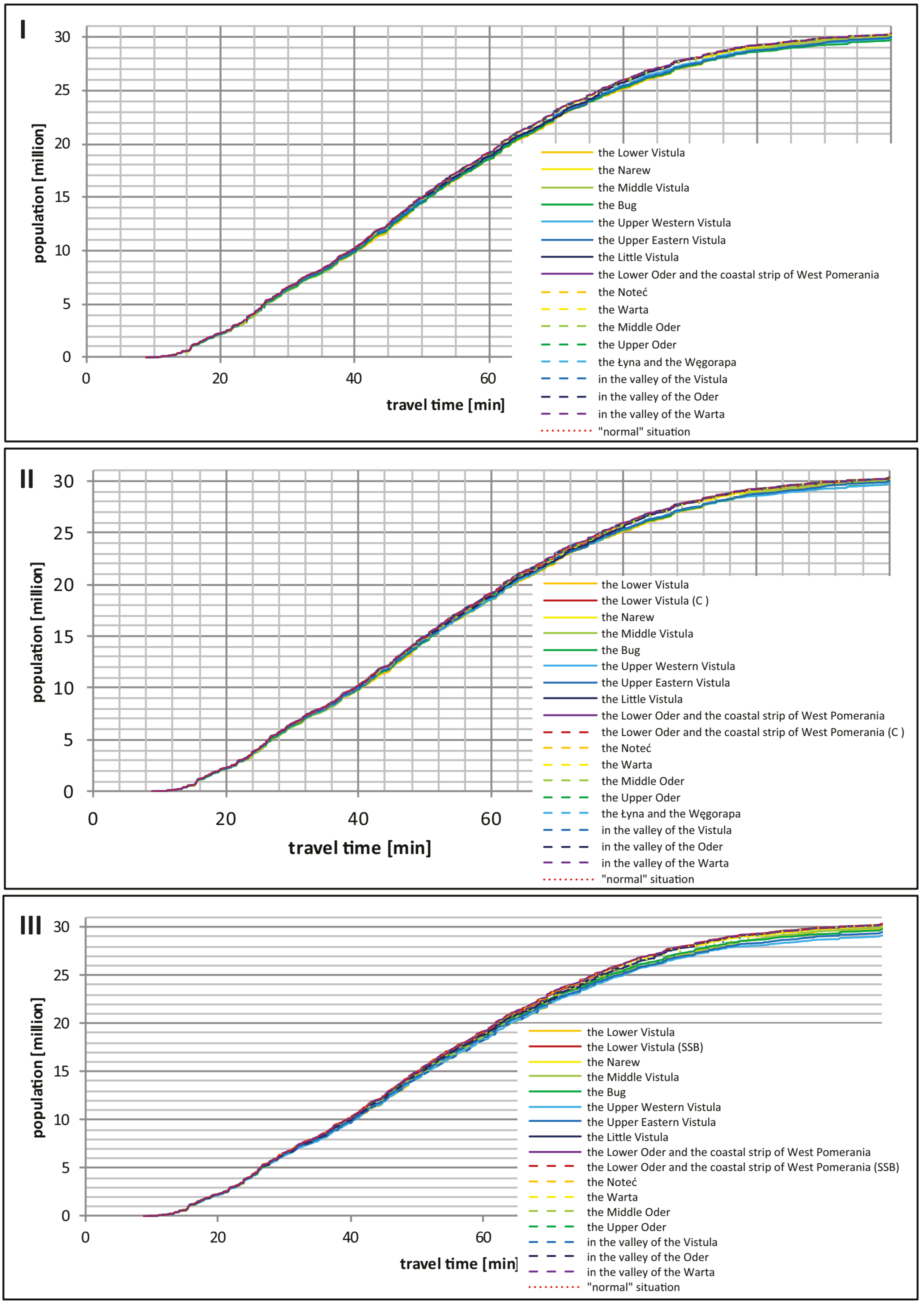
The scale of the expected increase in transport accessibility upon completion of a given investment project or the implementation of changes in transport organisation (road traffic organisational changes, etc.) are usually analysed in the literature on the subject. Less common are studies where analyses of accessibility are conducted to determine the magnitude of those factors which reduce the efficiency of the transport system. In the few publications which adopt this approach, drops in accessibility may reflect the effects of the emergence of administrative barriers, e.g., when state borders are closed (Jacobs-Crisioni and Koomen 2017, Rosik et al. 2020b, Wells, Sah and Moghadas 2020, etc.). Although common sense prompts one to assume a positive impact of the accessibility vector as a result of new road infrastructure, it should not be taken for granted, as accessibility may actually fall (e.g., when a far greater number of users than originally projected begin to travel along a new road). Indeed, the complex nature of any given factor in analysing changes in accessibility can produce quite unexpected results.

The relevance of developments in road infrastructure in shaping socio-economic potential at various spatial scales has been repeatedly stressed in studies. Infrastructural developments may not only improve the accessibility of regions and workplaces, but also reduce congestion, the operating costs of transport modes and travel time (Komornicki et al. 2010, Pawlak and Brdulak 2018). An equally broad spectrum of effects (though detrimental) can therefore be expected when a factor occurs that renders a section of road infrastructure partially or completely inoperable. This may result in a temporary drop in productivity or impede the competitiveness of businesses. The social aspect of the reduced accessibility that accompanies disruptions to normal operation of the road network must also be taken into account, since even a temporary lack of access to public services, resulting from disruption to its territorial cohesion, may intensify transport exclusion in areas where, even during a "normal" situation, the transport system is insufficient to meet the needs of its users. The impact of investments in road infrastructure on transport accessibility and travel time are key factors in assessing how effective they are. Therefore, a decision was made to assess the effects of flooding on passenger road transport using these two factors. Simulations for disruptions to the road network under different flood scenarios generated information on their "outcome," i.e., drops in accessibility and increases in road network load along some sections of the network. They also revealed that this "outcome" can emerge in locations distant from those directly affected by the flood itself.

The occurrence of a flood and the accompanying disruptions to the road network rarely lead to the necessity to permanently change the course of road sections. This only happens in the event of extensive damage to the infrastructure, or when a given section has been directly affected by flooding on a number of occasions, in which case, the need to reroute the course of the road infrastructure increases (Potrykowski and Taylor 1982), e.g., a longer stretch of road must be built to circumvent areas at risk of recurrent flooding. It is much more common, however, that only a temporary closure of a network segment occurs (until the hazard recedes and any damage is repaired). Whether any extension to the journey for road users is permanent or temporary, it results in a drop in the efficiency of the road system, i.e., a decline in transport-settlement efficiency (Śleszyński 2014). Śleszyński (2014) addresses time efficiency, defining it (for the road-settlement system) as a ratio of the expenditure incurred on investment projects versus the achieved travel speeds and, consequently, travel times. These expenditures on investments may be assessed from different perspectives; for instance, Śleszyński lists financial and environmental. If, however, the length of the road sections closed due to a flood is regarded as an expenditure, e.g.., as equal to the other flood-related impacts on the road transport system, and juxtaposed with the losses expressed as increased travel times and decreased accessibility, it is possible to determine the "effectiveness" of the different flood scenarios, perhaps better phrased as "destructiveness" or "harmfulness", since the term "effectiveness" may be inappropriate in this context.

The flood-related increase in travel times for passenger road transport was measured through an isochronous and cumulative approach. The potential inundation of or "cutting-off" of road network sections has an impact on travel times both to the nearest county seats and provincial capitals. However, detailed analyses (Chapter 6) indicate that, for the majority of simulated flood scenarios, travel time increases do not exceed the 15-minute interval for county seats or the 30-minute interval for provincial capitals. This stems not only from the relatively broad choice of alternative routes, the selection of which does not entail unacceptable increases in travel times, but also from the location of county seats and provincial capitals. Access to the next nearest city of a comparable rank and size when the usual route to the closest is shut requires a smaller increase in travel time when compared to that which would occur for a diversion route to the normal destination during flood-related disturbances. Śleszyński and Kretowicz (2016), as well as Komornicki et al. (2018) employed a cumulative approach to assess the effects of road investments on spatial accessibility on a regional and national scale. While assessing and monitoring changes in accessibility, Komornicki et al. (2018) applied 60-minute and 90-minute isochrones for county seats and provincial capitals, respectively, justifying them by the pull of the labour market and the temporal distance for "relatively convenient" trips for high-order services. The study presented in this monograph utilised the 60-minute isochrone to study changes in accessibility for county seats, whereas for provincial capitals the value was increased to 120 minutes so as to capture even the furthest possible increments in travel time (Figure 8.1).

For provincial capitals, the most serious negative effects for temporal accessibility would be caused by a complete breach of stopbanks in the water region of the Upper Western Vistula. This scenario involves a 3.31% drop in the population within the range of the 90-minute isochrone. As a result, more than 1.1 million people would be deprived of relatively convenient access to the nearest provincial capital, a value that should be considered high. In comparison, the study by Komornicki et al. (2018) revealed that there would be a 1.8% increase in the percentage of population covered by the 90-minute isoline of the commuting time to provincial capitals between 2013 and 2023. Flood-related drops in the water region of the Lower Vistula are considerably closer to this value, as it would exclude 2.13% of the baseline population from the 90-minute isochrone of commuting time for the scenario of a flood with 10% probability of occurrence and a further 0.54% for a 100-year fluvial flood. These are the maximum drops for these flood probabilities. For a coastal flood, however, declines in the population percentage would not exceed 0.30% of the baseline value. The study by Komornicki et al. (2018) on the accessibility of provincial capitals within the 60-minute isochrone showed that it would affect 5.6% more of the population in 2023 than it did in 2013. However, even the most far-reaching flood-related disruption to the road network falls significantly short of such values for the 60-minute isochrone. The highest recorded drop of 3.51% was observed following a flood that would cause a complete breach of stopbanks in the water region of the Lower Vistula. The 10-year and 100-year floods in the water region of the Bug would result in changes in the 60-minute isochrone that would omit a large population, i.e., 2.40% and 3.31% of the baseline value, respectively.



I – 10% probability, II – a fluvial or a coastal flood (C) with a 1% probability, III – a complete breach of stopbanks (SB) or a complete breach of the protective structure of the service strip (SSB)

Figure 8.1. Temporal cumulative accessibility by population and travel time to provincial capitals under different simulated flood scenarios in Poland in 2019

Source: own elaboration

In comparison to changes in the coverage of the 90-minute isochrone, a coastal flood would clearly have a greater impact on 60-minute accessibility to provincial capitals, although this would still be small and would not exceed 0.62% of the population base. An equally low drop in the temporal cumulative accessibility by population is observed for county seats.[1] Even with a complete breach of stopbanks in the water region of the Upper Western Vistula, only slightly more than 200,000 people (0.54%) would no longer be covered by the 60-minute commute isochrone to the nearest county seat. The consequences of the other flood scenarios considered in this context do not exceed a 0.36% decrease in population against the baseline figure, and in a number of cases (e.g., a coastal flood) no change at all is observed.

When cumulative accessibility to provincial capitals or county seats is reduced, this excludes the population from accessing some of their potential, e.g., their labour market or public services there. In the event of a flood, this is mostly temporary and does not permanently affect the transport behaviour of the population. However, in areas where flooding has the most adverse effects for travel times, it is advisable to monitor how robust road infrastructure is to the impact of floodwaters. Changes in population in areas at great risk of flooding should also be regularly monitored, as the level of exclusion is likely to rise when population growth is not followed by the necessary infrastructural investments.

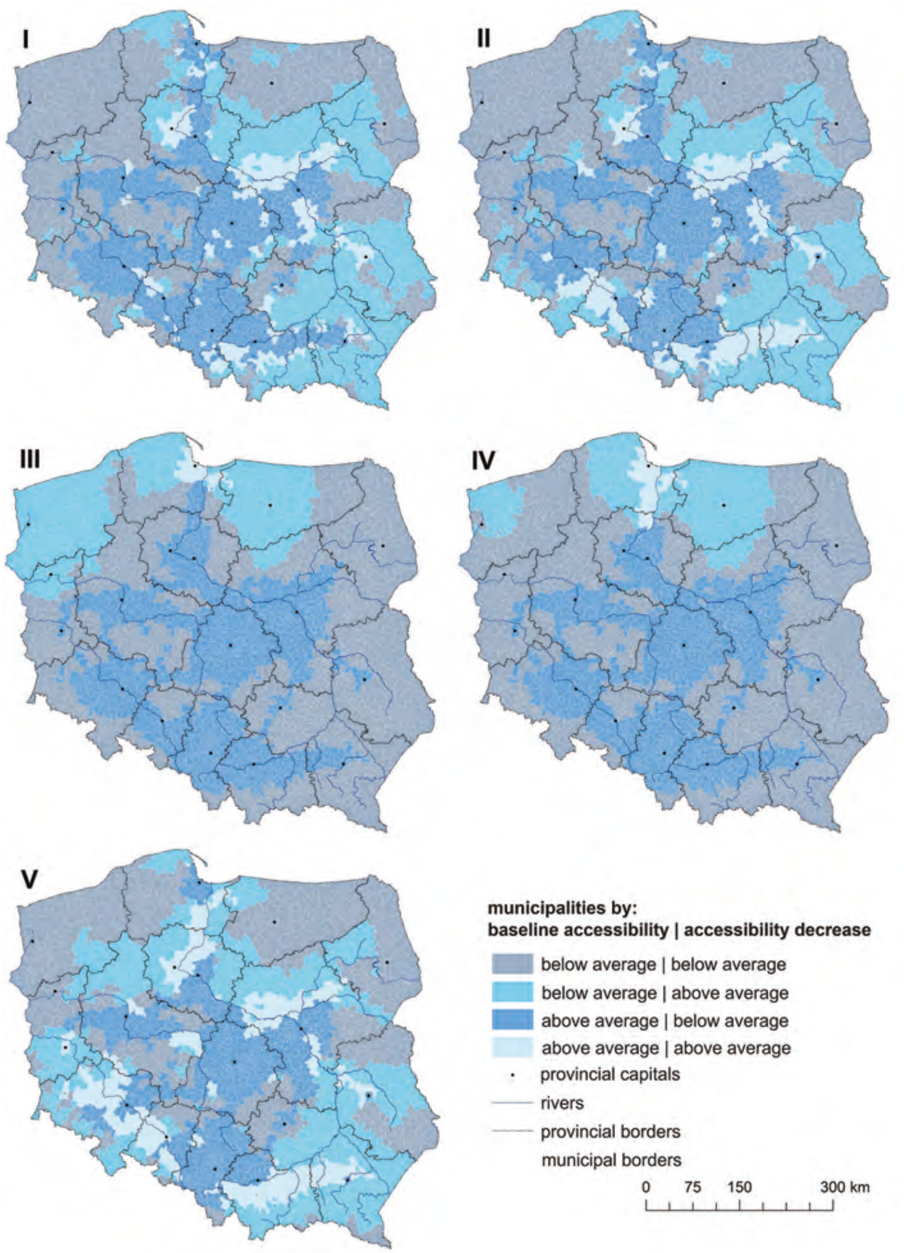
To limit reductions in the cumulative accessibility indicators, it is imperative to increase the robustness of road infrastructure, primarily to ensure access to provincial capitals. Since these centres have significant demographic potential, it may dramatically increase the number of people excluded if the infrastructure is highly vulnerable to flooding. The investments for road infrastructure described by Komornicki et al. (2018) would, in all likelihood, reduce the negative effects of this kind. This would mean that some towns would be covered by spheres of influence of a greater number of neighbouring provincial capitals, and if access to a given town is difficult, its "role" may be substituted by another one, with no significant rise in travel costs for the road network users (substitutability is by no means complete though, as different towns and cities may perform different administrative functions). This would also allow the tempering of inequalities in development through higher accessibility to areas with greater levels of development (Domański 1997, Komornicki 2019) even when faced with obstacles, including non-typical events (e.g., floods). In this context, the idea postulated by Komornicki et al. (2018) to route expressways in a way that allows them to perform an intra-regional role has great merits. This results from the high robustness of expressways (which also applies to the civil engineering structures thereon) to the effects of flooding, and secondly, from their performance parameters. For short trips in particular, these roads enable users to bypass areas at risk, while still being able to travel freely

[1] Graphs depicting temporal cumulative accessibility by population and travel time to county seats under different simulated flood scenarios are provided in Annex (Figure A.1).

even when faced with heavy traffic, and without having to make major diversions thanks to the relatively high density of junctions convenient to sub-regional centres (including county seats). The value of this solution is further confirmed by the fact that polarisation of accessibility is increasing on a regional or local scale, since the ease of reaching a given destination frequently depends on its location in relation to the nearest point (junction) where it is possible to join roads with the highest parameters (e.g., motorways) (Komornicki 2019).

In order to simultaneously address the impact of flooding on the components of transport and population, a synthetic, potential-based measure of changes in the transport system was employed. The magnitude of the observed changes in the relationships between individual transport regions and all other areas under study (including the changes caused by the concurrent reduction of potentials and increasing travel times due to a flood) reveals the significance of this factor for the efficiency of road transport in Poland. A number of authors (Li, Cao, Huang 2012; Rosik and Stępniak 2015; Jacobs-Crisioni, Silva and Lavalle 2016; Komornicki et al. 2018; Stępniak and Rosik 2018, etc.) have emphasised the strong correlation between demographics and infrastructure in shaping accessibility, which is also confirmed in flood impact analyses.

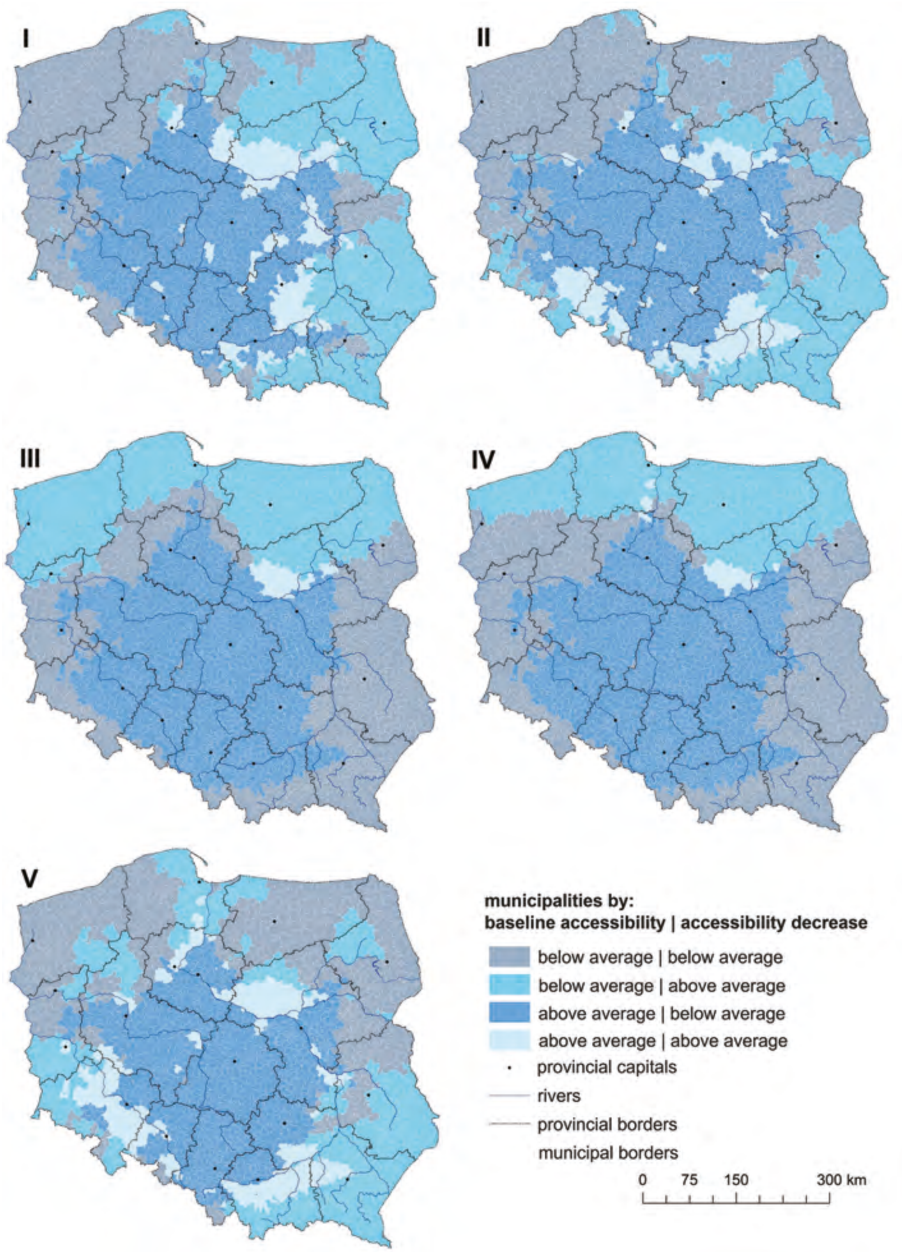
The starting point for investigating changes in accessibility, and, subsequently, for identifying areas where reductions are particularly problematic, was the determination of the basic spatial distribution of potential for short and long trips. The returned results largely confirm previous studies in this matter (e.g., Stępniak and Rosik 2016, Komornicki et al. 2018). For short trips in particular, two areas are clearly visible where the highest levels of accessibility accumulate – in the Łódź–Warsaw axis, and the Upper Silesian conurbation-Kraków axis. High levels of accessibility are also observed locally in the vicinity of Poznań, Tri-City (Gdańsk–Gdynia–Sopot), and Wrocław, within the "corridors" of increased accessibility leading towards Łódź and Silesia. For long trips, these local, isolated "islands" of high accessibility are still preserved, forming a distinct core with regard to the network of infrastructurally-connected cities as indicated in the National Emergency Management Plan 2030, which covers the area between the provincial capitals of Masovia, Lesser Poland, Lower Silesia, Greater Poland, and Pomerania, extending slightly eastwards towards Białystok, Lublin, and Rzeszów, and westwards towards Lubuskie Province. Areas that remain problematic are: West Pomerania, Warmia-Masuria, the eastern edges of Podlaskie Province and Lublin Province as well as the southern part of Podlaskie Province. To make the division of municipalities by baseline accessibility more readable, they were classified by their average value (Figures 8.2 and 8.3) and also by the drop observed under the different flood scenarios based on the findings presented in Chapter 6. As a result, four types of municipalities were identified with regard to the level of basic potential accessibility and the magnitude of its reduction for short and long trips, with special attention given to settlement units where low basic accessibility co-occurred with a large drop during a flood.



I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 8.2. Classification of municipalities by level of basic potential accessibility and the magnitude of its decrease for short trips following a flood in the different scenarios in Poland in 2019

Source: own elaboration



I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 8.3. Classification of municipalities by level of basic potential accessibility and the magnitude of its decrease for long trips following a flood in the different scenarios in Poland in 2019

Source: own elaboration

Regardless of trip length, a fluvial flood would cause a particularly unfavourable situation for transport accessibility in the northern part of Masovian Province and a large territory of provinces in eastern Poland. What matters greatly in this perspective is the relative increase in road accessibility expected in the macro-region of eastern Poland by 2023, as argued by Komornicki et al (2017). It is expected that the emerging network of infrastructurally-connected cities will include Rzeszów, Lublin, and also (partially) Białystok. Areas with a low basic level of accessibility and associated high flood-related reduction include the southern part of Lesser Poland, as well as areas that fall into this category only when faced with a complete breach of stopbanks: namely, northern Greater Poland, Silesian Lowland, Sudeten Foothills, and the Lubusz Lake District. In contrast, a flood in West Pomerania and Warmia-Masuria would not have any particular effect on the already low basic level of accessibility there. In most cases, the negative flood-related consequences for transport accessibility do not significantly exacerbate the barriers arising from transport policy, as discussed by Śleszyński et al. (2019). "Detached in terms of transportation from the economic and decision-making centre of the country" (Śleszyński et al. 2019, p. 21), Szczecin is not exposed to a significant drop in accessibility in the event of a fluvial flood, however, it remains within the sphere of above-average drops in accessibility due to coastal flooding, along with the towns in Pomerania and Warmia-Masuria, although the drops observed for these flood scenarios take very small percentage values.

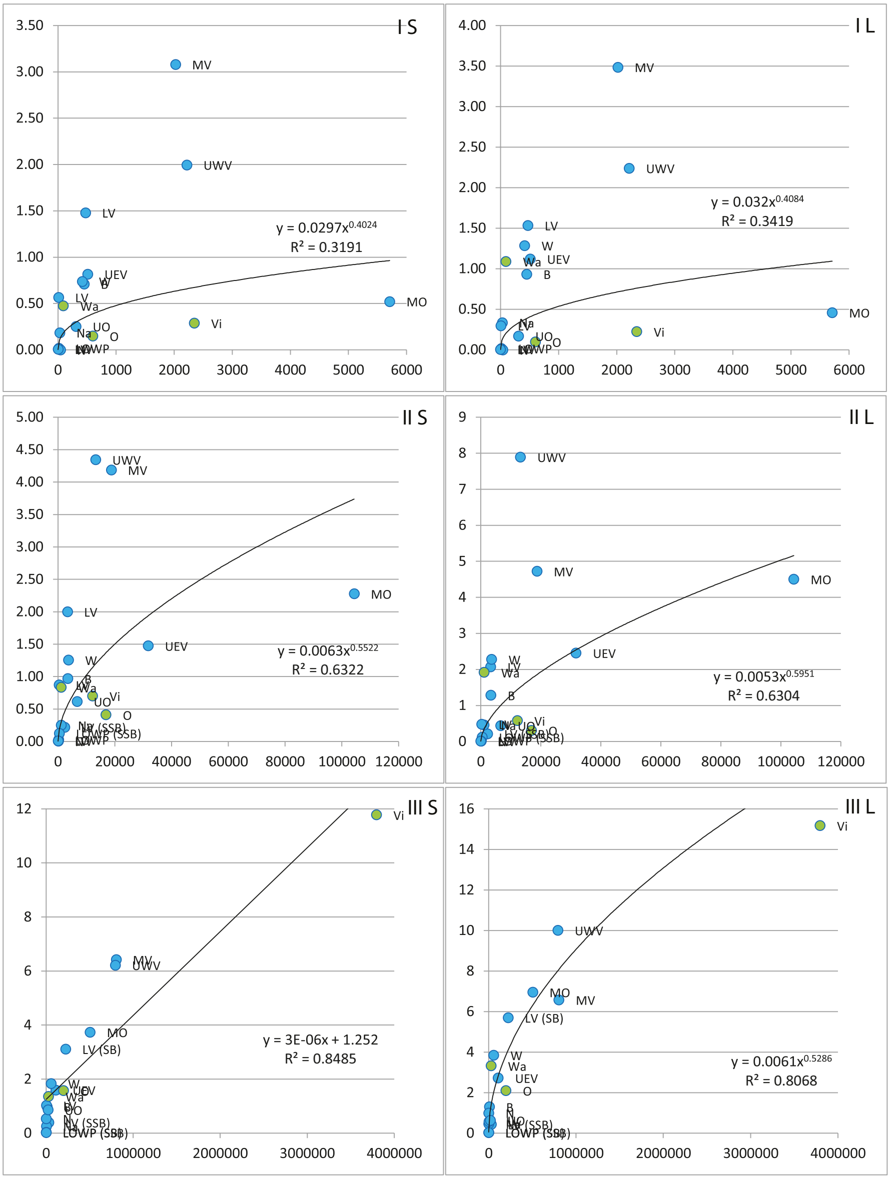
Potentially, locations characterised by peak base values of accessibility may also experience a significant decrease in value. This particularly applies to municipalities north and north-west of Warsaw, in the Bydgoszcz area (for long trips), and territories adjacent to the A4 motorway along its Wrocław–Opole and Kraków–Rzeszów sections. What appears symptomatic is the occurrence of high absolute drops in accessibility in areas that are connected to cities boasting high (e.g., demographic) potential on account of road infrastructure that allows high travel speeds when this potential is reduced or where the road infrastructure is highly susceptible to the destructive effects of a flood on sections located close to these cities. Hence, such disturbances result in a reduction of potential within the entire area serviced by a given road. The scope of this negative impact is much smaller, however, when the same road is inundated but the flooding affects sections that are located closer to smaller towns, i.e., settlement units with less demographic potential.

It is considerably easier to determine the magnitude of the flood-related consequences for passenger road transport when the results obtained are compared against the findings of analyses of changes in transport accessibility in Poland conducted primarily for the purpose of infrastructure investments. The results of the detailed analyses conducted for short trips (Chapter 6) indicate that – depending on the area affected by flooding – the maximum nationwide drops in accessibility range from just over 5% for the basin of the Oder to ca. 8% for the basin of the Vistula. For long trips, the maximum falls increase to just under 7% and slightly over 10% for the Oder and the Vistula, respectively. In comparison, Komornicki et al. (2017) indicated that between 2013 and 2023, the Road Transport Accessibility Index would increase by over 19% nationally (baseline as of 2013) following the implementation of new road infrastructure. Studies on the impact of selected road corridors on the environment and socio-economic development of adjacent areas (Komornicki et al. 2015) showed that infrastructure investments between 2004 and 2013 (baseline as of 2004) had resulted in an increase in the national level of potential accessibility nearing 20% and just below 17.5% for short and long trips, respectively. Although the absolute values of changes in accessibility obtained from the flood simulations are clearly lower, they may still be considered alarming given the range of infrastructural investments that the analyses took into account. The most severe flood scenarios for accessibility may periodically lead to its reduction by a value clearly higher than the gains accompanying the completion of the following motorway sections: Wrocław-Opole (A4) and Pruszcz Gdański-Grudziądz (A1) (Komornicki et al. 2015). However, one must not forget that disturbances of this magnitude are only possible for a very limited number of flood scenarios under study.

Assessment of the impact that a flood would have on passenger road transport should be supplemented by a measurement of the scale of its direct effect for individual scenarios. For this purpose, the Road Transport Flood Exposure index (RTFE) was introduced, which took into account the population component as well as the quantitative and qualitative properties of the transport component. The RTFE is a product of the length of roads (in kilometres), the maximum permissible travel speed along their segments (in km/h, compliant with the traffic code), and the population of flood hazard areas under a given scenario. Figure 8.4 shows the RTFE values juxtaposed with the values of the Overall National Accessibility Effect indicator (ONAE) in relative terms. In absolute terms, it becomes the population-weighted (P) difference in the accessibility level on a national scale between a given analysed flood scenario (A_S) and the "normal," baseline situation (A_B) (Stępniak and Rosik 2013):

$$\text{ONAE} = \frac{\sum A_{iS} * P_i}{\sum P_i} - \frac{\sum A_{iB} * P_i}{\sum P_i}$$

In relative terms, however, it indicates the percentage value of this difference within the baseline value (Figure 8.4).



horizontal axis – RTFE index; vertical axis – ONAE indicator in relative terms [%]

Figure 8.4. Correlation between the magnitude of the exposure of the road transport system to flooding under the different scenarios[2] and the accompanying countrywide impact on accessibility for short (S) and long (L) trips in Poland in 2019

Source: own elaboration

[2] I – 10% probability, II – a fluvial or a coastal flood (C) of 1% probability, III – a breach of stopbanks (SB) and a breach of the protective structure of the service

For short trips, the vast majority of flood scenarios yield a relative ONAE value below 1%. A flood in the water regions of the Middle Vistula and the Upper Western Vistula would be particularly problematic for accessibility, regardless of the applied flood probability. For simulations of 10-year and 100-year floods, however, it is the water region of the Middle Oder that suffers from the highest exposure of the road transport system (the highest RTFE values), although this does not translate into proportionally severe changes in accessibility, as the ONAE value never exceeds 2.5%. By way of comparison, the relative change in the ONAE following the incorporation of the A2 Łódź-Warsaw motorway section into the Polish road network amounted to 1.49% and 1.19% for domestic short and long trips respectively, as shown by Stępniak and Rosik (2013). The implementation of the section of the A2 motorway from the Polish-German border to Nowy Tomyśl produced considerably lower results of 0.06% and 0.05% for domestic short and long trips, respectively.[3]

A significant ONAE increase of several percent is observed for simulations that involve a complete breach of stopbanks. The ONAE value and the magnitude of the impact on accessibility measured for a flood on the Vistula prove that this scenario would have the greatest impact on transport system. For long trips, the results indicate that a flood in the water region of the Upper Western Vistula would be particularly problematic.

The analysis of the flood-related effects on passenger road transport with regard to accessibility was supplemented by research into the extent of its differentiation accompanying the various scenarios under study. The polarisation of accessibility, even if temporary (Komornicki et al. 2018), is a sign of areas with limited access to public services, which may, over time, translate into lower living standards for this, transport-excluded, population. In other words, the occurrence of flood-related obstacles may periodically exacerbate transport inequality, as described by Komornicki (2019). Any temporary, flood-related increase in spatial differentiation of accessibility is likely to become less impactful once the planned major road investments (including those related to other modes of transport) have been completed, leading to a reduction in the basic level of accessibility polarisation.

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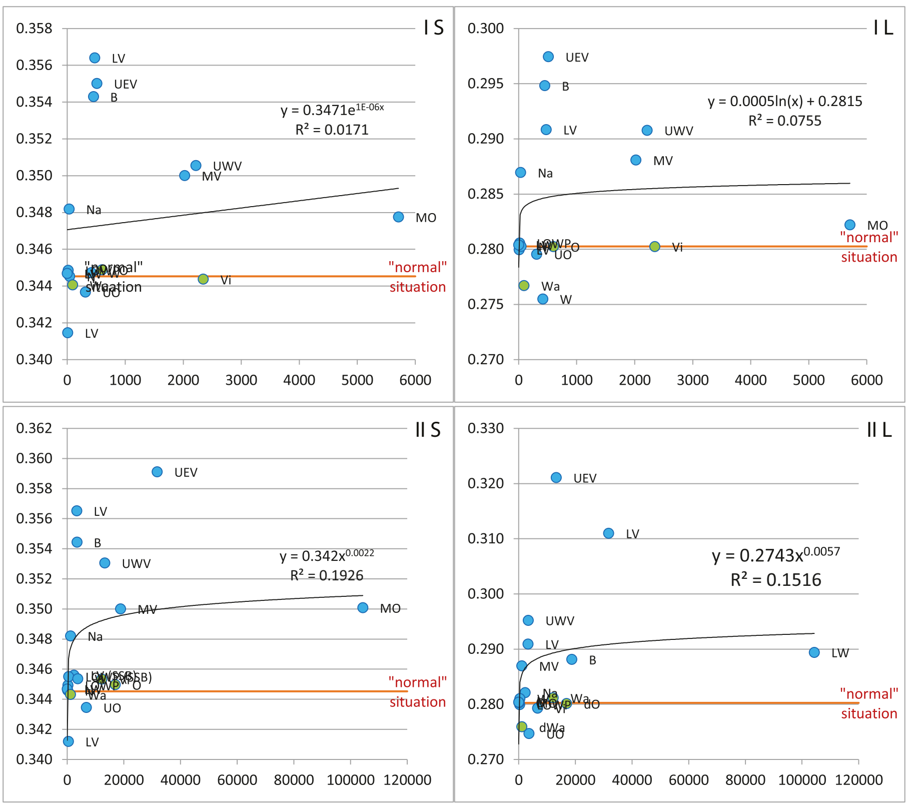
strip (SSB); water regions: LV – the Lower Vistula, Na – the Narew, MV – the Middle Vistula, B – the Bug, UWV – the Upper Western Vistula, UEV – the Upper Eastern Vistula, LV – the Little Vistula, LOWP – the Lower Oder and the coastal strip of West Pomerania, N – the Noteć, W – the Warta, MO – the Middle Oder, UO – the Upper Oder, LW – the Łyna and the Węgorapa; main rivers (green dots): Vi – the Vistula, O – the Oder, Wa – the Warta

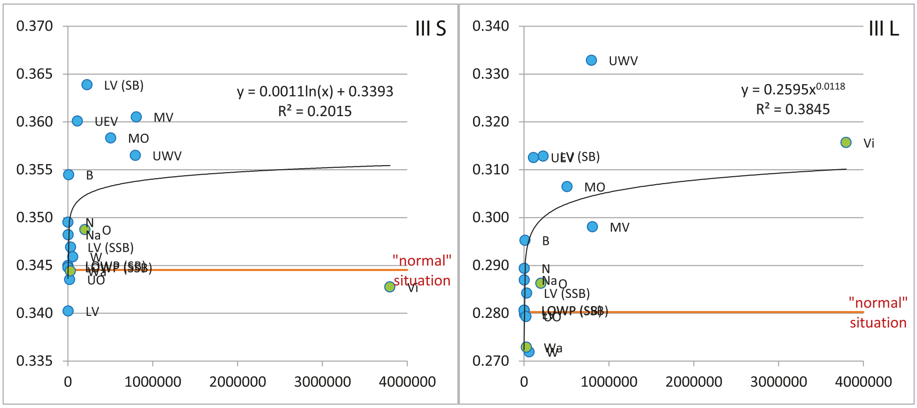
[3] The following distance decay parameters were adopted: for short trips (average travel time of 30 minutes), $\beta = 0.023105$; for long trips (average travel time of 120 minutes), $\beta = 0.005775$.

The impact on territorial cohesion was measured using the Potential Accessibility Dispersion index (PAD), which is the quotient of the standard deviation of the accessibility indicator (SD_A) and the population-weighted (P) average value of the indicator calculated for the level of municipality (A_i) (Ortega et al. 2012, Stępniak and Rosik 2013, Rosik et al. 2015):

$$\mathrm{PAD} = \frac{SD_{A_i}}{\frac{\sum A_i * P_i}{\sum P_i}}$$

The lower the PAD values, the less polarised the study area is for the distribution of accessibility. Thus, from the perspective of analyses of the effects of flooding on passenger road transport, any increase in the PAD value following a flood in a given scenario is an adverse phenomenon (Figure 8.5).





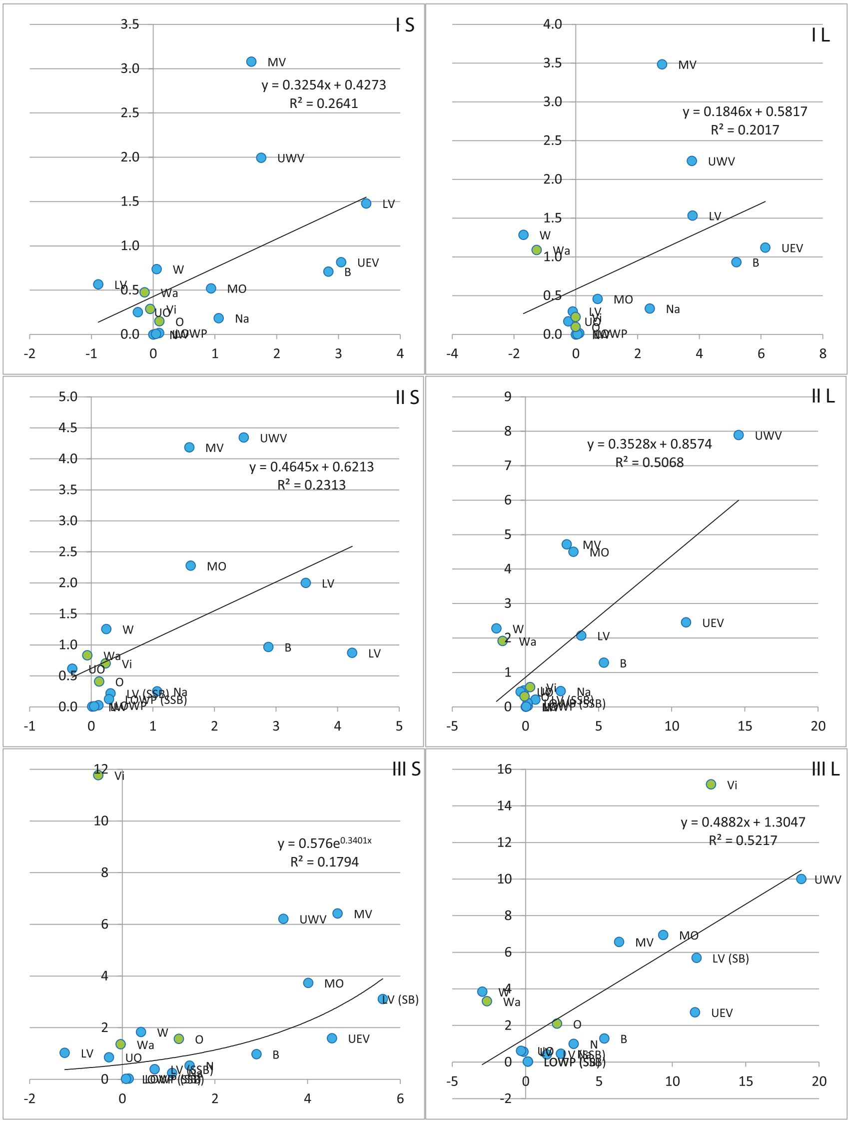
horizontal axis – RTFE index, vertical axis – the differentiation of accessibility (Potential Accessibility Dispersion index, PAD)

Figure 8.5. Correlation between the magnitude of road transport exposure to flooding in the different scenarios[4] and the accompanying level of spatial differentiation of accessibility for short (S) and long (L) trips in Poland in 2019

Source: own elaboration

The flood-related impact on the differentiation of accessibility was also analysed in dynamic terms by introducing an index of its percentage shift in relation to the value typical for a "normal" scenario. Figure 8.6 shows this index juxtaposed with the ONAE indicator in relative terms so that the correlation between the "strength" of the impact on accessibility and the differentiation in the level of its consequences could be examined. As a result, it became evident that there is no clear proportionate correlation between the two. An increase in the impact on accessibility on a national scale is usually accompanied by an increase in its polarisation, but there are also flood scenarios, e.g., the 10-year flood in the water region of the Little Vistula, which produce the opposite effect. Regardless of the analysed trip length and flood probability, it is apparent that the occurrence of a flood in the basin of the Vistula (especially in the water regions of the Lower Vistula, the Upper Western Vistula, and the Upper Eastern Vistula) would usually cause the greatest drops in accessibility on a national scale and would significantly increase its polarisation.

[4] I – 10% probability, II – a fluvial or a coastal flood (C) of 1% probability, III – a breach of stopbanks (SB) and a breach of the protective structure of the service strip (SSB); water regions: LV – the Lower Vistula, Na – the Narew, MV – the Middle Vistula, B – the Bug, UWV – the Upper Western Vistula, UEV – the Upper Eastern Vistula, LV – the Little Vistula, LOWP – the Lower Oder and the coastal strip of West Pomerania, N – the Noteć, W – the Warta, MO – the Middle Oder, UO – the Upper Oder, LW – the Łyna and the Węgorapa; main rivers (green dots): Vi – the Vistula, O – the Oder, Wa – the Warta.



horizontal axis – relative change in the differentiation of accessibility (Potential Accessibility Dispersion index, PAD) against the "normal" situation [%], vertical axis – ONAE indicator in relative terms [%]

Figure 8.6. Correlation between the nationwide impact of flooding on accessibility in the different scenarios[5] and the accompanying changes in the spatial differentiation of accessibility for short (S) and long (L) trips in Poland in 2019

Source: own elaboration

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[5] I – 10% probability, II – a fluvial or a coastal flood (C) of 1% probability, III – a breach of stopbanks (SB) and a breach of the protective structure of the service

The magnitude of the increase in the differentiation of accessibility can be captured by comparing it with the results obtained for other factors affecting the operation of the road transport system, i.e., investments in road infrastructure. As reported by Stępniak and Rosik (2013), the construction of the A2 motorway sections between Łódź and Warsaw and from the Polish-German border to Nowy Tomyśl resulted in a change in the differentiation of accessibility by 0.70% and –0.13% for short trips, and 0.97% and –0.14% for long trips, respectively. Rosik et al. (2015) and Stępniak and Rosik (2016) prove that the decade after Poland's accession to the EU (when many motorway and expressway sections were built) resulted in a 0.44% increase in the PAD index.[6] A similar change in the PAD value for short trips (up to 1%) would result from a 10-year flood in the water region of the Middle Oder, while a flood with a 10% probability of occurrence in the water region of the Upper Western Vistula would lead to a nearly 2% increase in the differentiation of accessibility. A slightly higher figure (2.13%[7]) was reported by Komornicki et al. (2018) when studying the impact of road infrastructure investments between 2004 and 2023,[8] showing that the highest figure (3.46%[9]) was found for the period between 2004 and 2006. Such a magnitude of change in the differentiation of accessibility for short trips would be caused by a 100-year flood in the water regions of the Lower Vistula and the Upper Western Vistula following a complete breach of stopbanks. The observed changeability of the dispersion indexes proves that the performance of road transport when affected by floods generally results in an increase in the polarisation of accessibility. It is, therefore, vital to ensure the high robustness of the infrastructure for locations that incorporate centres with the greatest demographic potential where flooding may cause the greatest disparities in the level of transport. This is true even if their basic accessibility differs from that typical of large urban centres in the emerging network of infrastructurally-connected cities. This will be of particular importance once

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strip (SSB); water regions: LV – the Lower Vistula, Na – the Narew, MV – the Middle Vistula, B – the Bug, UWV – the Upper Western Vistula, UEV – the Upper Eastern Vistula, LV – the Little Vistula, LOWP – the Lower Oder and the coastal strip of West Pomerania, N – the Noteć, W – the Warta, MO – the Middle Oder, UO – the Upper Oder, LW – the Łyna and the Węgorapa; main rivers (green dots): Vi – the Vistula, O – the Oder, Wa – the Warta.

[6] For domestic trips, a parameter β of 0.013862 was adopted, for which the attractiveness of the destination drops by 50% for a trip that lasts 50 minutes.

[7] The author's own calculations based on data in Komornicki et al. (2018).

[8] For domestic travel, a parameter β of 0.023105 was adopted, for which the attractiveness of the destination drops by 50% for a trip that lasts 30 minutes.

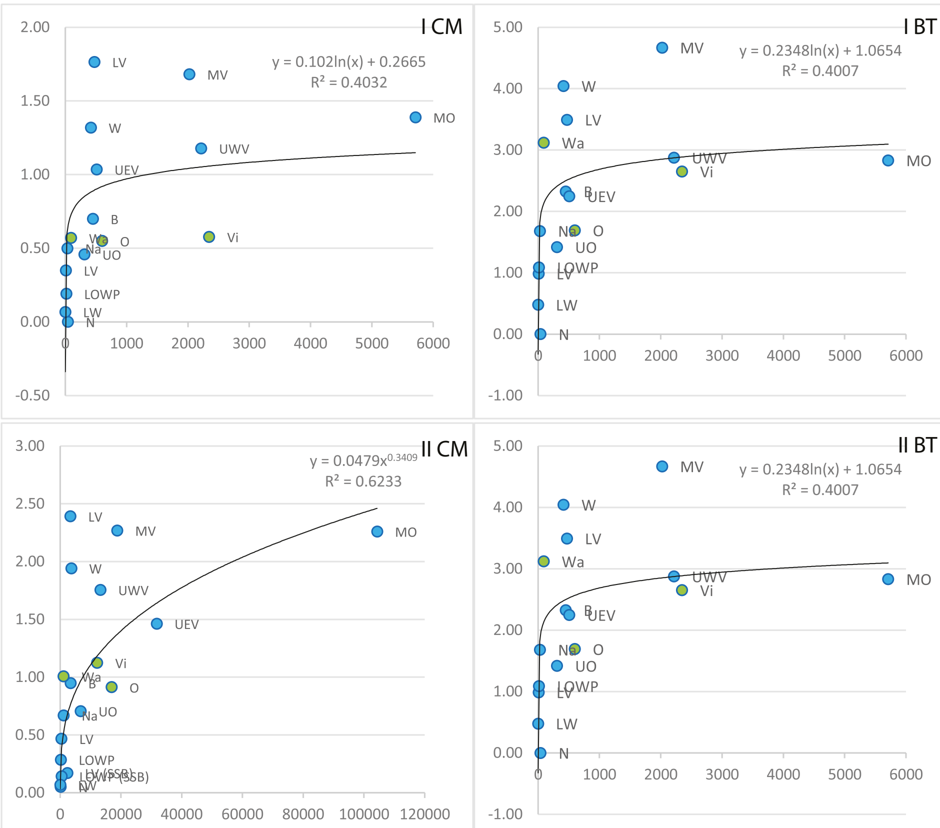
[9] The author's own calculations based on data in Komornicki et al. (2018).

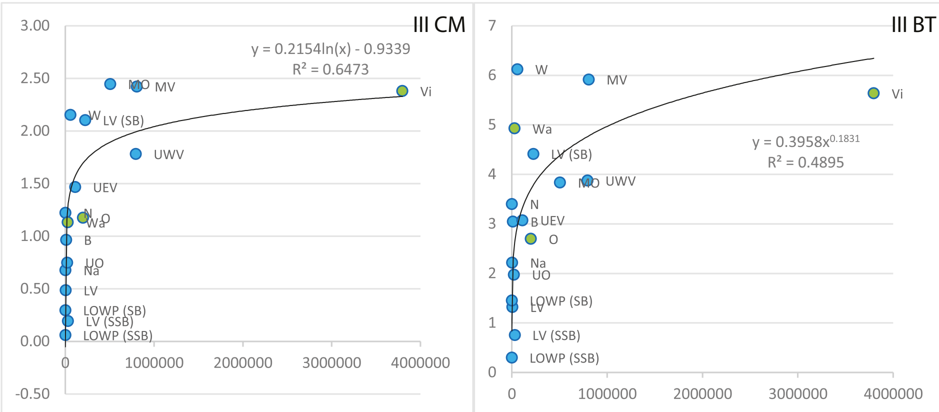
all key infrastructural investments have been completed. Then, the reduction in demographic potentials (incorporated into analyses of flood-related changes in transport accessibility) will depend more on the potential of the transport regions than on road closures due to a flood.

8.2. Effects on road network load

Besides the impact on accessibility, changes in the operation of the transport system resulting from disruptions to the national road network are also examined using data on vehicle traffic volumes (Komornicki et al. 2015, 2017, Rosik and Kowalczyk 2015, etc.). Typically, these analyses are based on secondary data from periodic surveys of road network load, e.g., the General Traffic Censuses (GTC). The juxtaposition of the results obtained for the different periods makes it possible to access data on the magnitude of changes in traffic volumes and their distribution over a network which is usually only represented by major elements (in the GTC, these are extra-urban sections of national and regional roads). Although this approach makes it possible to observe changes on a national scale, it does not allow for the situation on local road networks to be monitored. Another difficulty is the presence of the many factors (infrastructural, demographic, economic, administrative, etc.) which determine the distribution of traffic on the road network during periods between consecutive surveys, especially if the applied research objective is to assess the impact of selected factors only. An alternative approach is to base the analysis on traffic models, where simulations conducted for a given transport system take into account not only traffic but also boundary and baseline conditions that describe the factor under study. However, this approach is most often applied in studies that focus on significantly smaller scales than a national one, i.e., changes in road network load are usually analysed at the scale of an urban road network or its selected sections (Karoń, Żochowska, and Sobota 2014, Bochniak and Krzaczek 2015, Budyn and Sowa 2016, Drabicki, Szarata and Kucharski 2018, Sarna 2018, etc.).

The simulations conducted to determine the flood-related impact on passenger road transport with regard to the road network load were performed in a manner that enabled its examination on the scale of the entire national road network, while taking into account factors whose impact on the transport system cannot be grasped by any regularly undertaken measurements (here: floods). The application of traffic simulation models also created an opportunity to "isolate" the distinctive responses of the road transport system to a flood, responses which may contribute to worsening road and traffic conditions, resulting in an increase in travel time, which, in turn, may manifest itself as deferred traffic (Lee, Klein and Camus 1999). The absolute changes in vehicle numbers on selected network segments observed in the simulation of individual flood scenarios stem from a spatial shift in trips (Figure 8.7). The incorporation of a temporal or modal shift should be the subject of further in-depth analyses, especially for those areas where the greatest spatial shifts have been observed. However, given the compulsory nature of the trips under study, the possibilities of postponing them are severely limited.





horizontal axis – RTFE index, vertical axis – percentage of the length of the road network sections on which an absolute increase in vehicle numbers occurred against the total length of the national road network [%]

Figure 8.7. Correlation between the magnitude of the exposure of the road transport system to flooding in the different scenarios[10] and the accompanying increases in road network load for commuting (CM) and business trips (BT) in Poland in 2019

Source: own elaboration

Comparison of the exposure index of the road transport system with the percentages of the length of road network sections on which an absolute increase in vehicle numbers occurred against the total length of the national road network for individual flood scenarios proves that flooding in the water regions of the Lower Vistula, the Middle Vistula, and the Warta would have particularly far-reaching consequences for the equilibrium of the transport system. Regardless of the trip motivation, there is an alarming disproportion between the scale of the direct impact of the flood and the magnitude of the consequences for changes in traffic volume. The resultant traffic distribution on the network due to flooding is also impacted by the drop in the number of trips for suppressed traffic (Szarata 2010). There are sections of the network where the observed drops in traffic

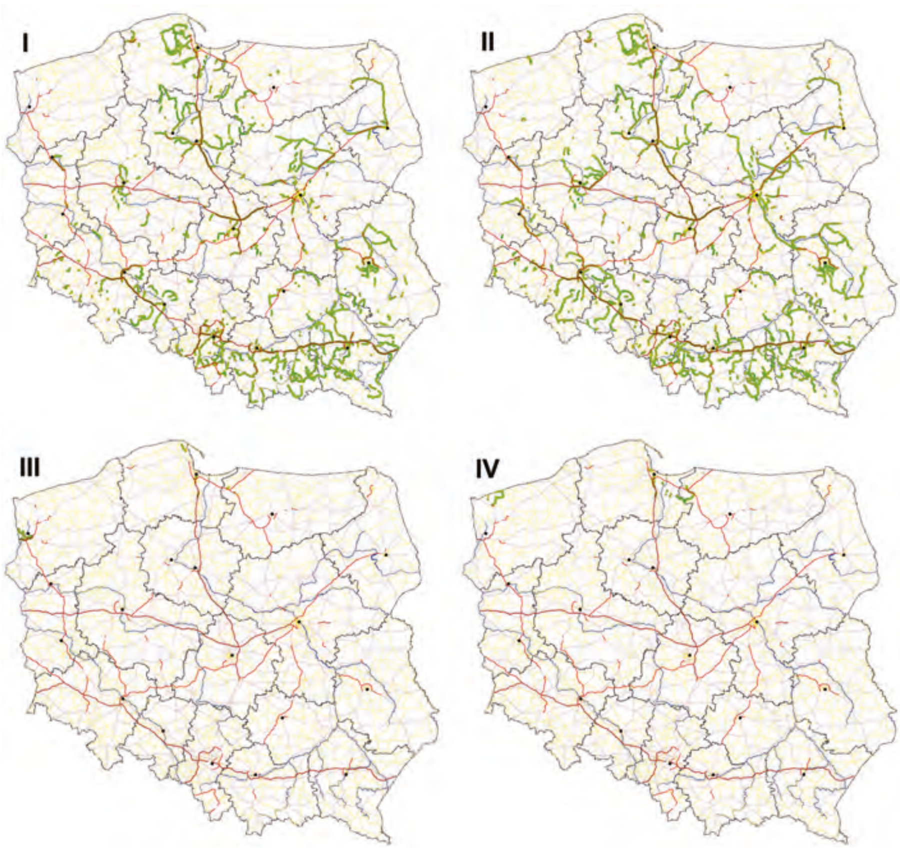
[10] I – 10% probability, II – a fluvial or a coastal flood (C) of 1% probability, III – a breach of stopbanks (SB) and a breach of the protective structure of the service strip (SSB); water regions: LV – the Lower Vistula, Na – the Narew, MV – the Middle Vistula, B – the Bug, UWV – the Upper Western Vistula, UEV – the Upper Eastern Vistula, LV – the Little Vistula, LOWP – the Lower Oder and the coastal strip of West Pomerania, N – the Noteć, W – the Warta, MO – the Middle Oder, UO – the Upper Oder, LW – the Łyna and the Węgorapa; main rivers (green dots): Vi – the Vistula, O – the Oder, Wa – the Warta.

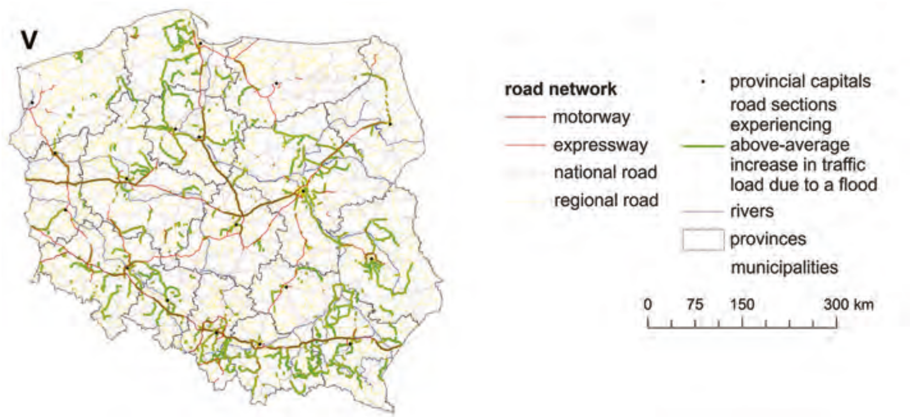
did not result from their closure but from them no longer being part of new optimum routes. The reduction of traffic-generating potentials applied in this study was designed to reflect the possible drop in or abandonment of commuting or business trips when people are in danger. In this context, it should be stressed that the phenomena discussed above, as well as the underlying causes of their occurrence, are usually of a temporary nature, and that any changes within the road network, or the inclination to travel, will only have a direct impact on traffic. Quoting the website Transport Publiczny, Drabicki, Szarata and Kucharski (2018) give the example of the Łazienki Bridge in Warsaw, which was closed to traffic abruptly in 2015. The nearly year-long shutdown of this important infrastructure only resulted in 50% of previous users choosing alternative bridges to cross the Vistula. The other 50% made a modal shift (i.e., they used alternative modes of transport), changed their trip destination, or simply did not travel.

The typically short-term nature of changes as an effect of floods, combined with the extreme circumstances under which they occur, is a major impediment in determining the possible changes in mobility (Litman 2017) typical for individual flood scenarios. Adopting demand at an unchanged level could lead to excessive divergences in the distribution of traffic when compared to the "normal" situation. Precise specifications would require surveys, which, at this scale of analysis, would be extremely time-consuming and cost-intensive (as confirmed by a pilot study). Therefore, an intermediate variant was introduced that makes demand slightly more flexible, and at the same time, is correlated with the attributes of road users (e.g., place of residence within areas at risk). Given the lack of data on the actual population that may be affected by a drop in mobility, simulation modelling that takes into account the factor of transport accessibility (Szarata 2013) may be a solution for determining the number of suppressed trips arising from individual flood scenarios. Under this approach, the drops in accessibility that characterise given transport regions occur as a result of increased travel times in the different flood scenarios and can be translated into a reduction in the number of trips for each region.

Closures of sections of the road network when they are inundated or "cut off" by floodwaters, combined with local capacity constraints and a reduction in traffic-generating potentials, resulted in changes in the volume of commuter traffic ranging from a few hundred vehicles for flood simulations for the basin of the Pregolya, to over 4,000 for the basin of the Oder, and almost 7,200 for basin of the Vistula. When business trips are taken into account, the changes in vehicle numbers in the basin of the Oder are only slightly amplified, yielding a maximum result of nearly 4,700. The change in motivation has a completely different effect on the magnitude of disturbances within the basin of the Vistula in the scenario of a complete breach of the stopbanks (which is most severe for the road network), yielding changes of almost 14,500 vehicles. By comparison, the Annual Average Daily Traffic (AADT) on extra-urban sections of regional roads (as shown in the 2015 General Traffic Census) was just over 3,500 vehicles per day (of which 83.8% were passenger cars), and over 11,000 vehicles per day for extra-urban sections of national roads (of which 71.7% were passenger cars). For the provinces within the basin of the Oder, the AADT ranged from over 1,700 (Lubuskie Province) to over 4,600 (Silesian Province) passenger cars per day for extra-urban sections of regional roads in 2015 (Opoczyński 2016ab). The observed flood-related changes in traffic volumes in the area do not exceed these values. The flood-related changes recorded in basin of the Vistula are closer to the 2015 AADT value for extra-urban sections of national roads. In the provinces within the basin of the Vistula, the AADT ranged from over 4,300 (Warmian-Masurian Province) to over 14,300 passenger cars per day (Silesian Province). The observed flood-related changes in traffic volumes in this area do not exceed these values either.

Simulating the changes in the transport infrastructure and traffic-generating potentials made it possible to identify road network sections with an above-average increase in traffic load for commuting and business trips (Figures 8.8 and 8.9).





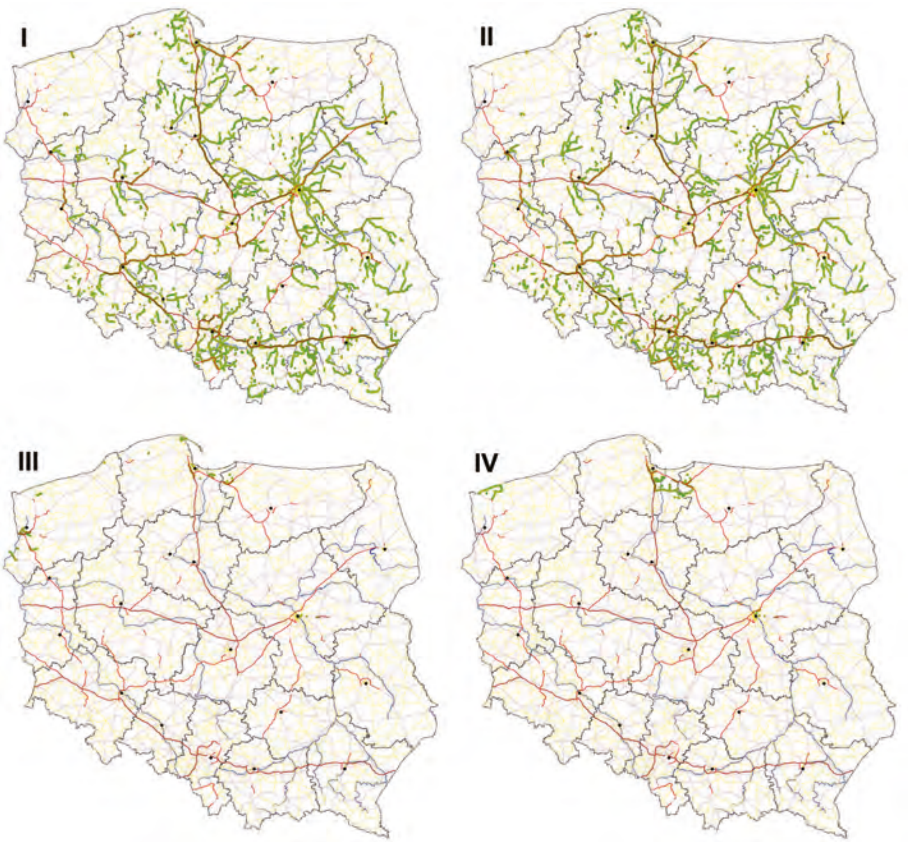
I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

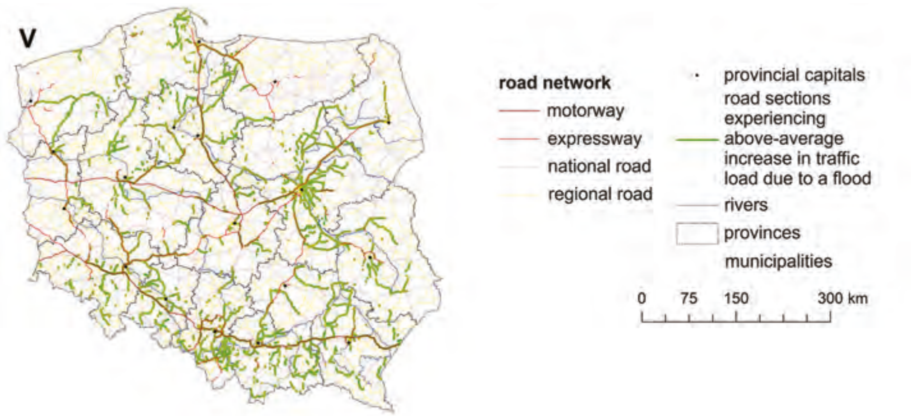
Figure 8.8. Spatial distribution of road network sections with an above-average increase in commuter traffic load due to a flood under a given scenario in Poland in 2019

Source: own elaboration

Whenever a trip is motivated by the need to reach the workplace, particularly high increases in vehicle numbers usually occur on those road network sections adjacent to large agglomerations – the absorptive labour markets of, primarily, Warsaw, Tri-City (Gdańsk–Gdynia–Sopot), Lublin, Poznań, Wrocław, and Opole – and the area to the south of the A4 motorway corridor. This confirms the validity of prioritising the implementation of road investment projects for those sections which are connected to large urban centres. In order to make the road transport system more robust to the occurrence of additional traffic flows caused by flooding, it seems justifiable to allocate funds for investments of those road sections (even of lower class) that direct traffic towards agglomerations, rather than split resources into numerous, often local, projects, e.g., on culverts or minor bridges that are at risk during floods. Studies show that the road network is often characterised by such a high number of optional travel routes that, although the inundation of one section may force users to look for a detour, they are not inclined to abandon their travel plans. This (usually local, limited and spatially diverted) traffic will eventually burden, in a cumulative manner, other network segments that lead directly to areas with a high density of workplaces.

Although the specific distributions of traffic that accompanies non-typical events should not be a determinant when planning future road infrastructure, they should be taken into account as extreme (boundary) values. For short trips (commuting to work), the completion of major road investments may, in the short term, not result in drastic changes in the pattern of road network sections with a higher than average increase in flood-related traffic load. In the short-term perspective, the new infrastructure will, however, lead to changes in those trips whose costs may decline (mainly travel time). When the road infrastructure investments have become fully operational, one may expect an accompanying increase in accessibility in the longer term, following a spatial rise in the impact exerted by job markets of large urban centres (often compensating for their lack of available workforce). As the investments in question are highly robust to flooding, they should ultimately contribute to a reduction in future changes in traffic volumes that accompany such non-typical events as a flood. Any uncertainty behind these predictions lies in the nature of this type of natural disaster itself and the changeability of its territorial range, often as a result of human interference in the natural environment, including through road infrastructure projects.





I – 10% probability, II – 1% probability (fluvial flooding), III – 1% probability (coastal flooding), IV – a complete breach of the protective structure of the service strip, V – a complete breach of stopbanks

Figure 8.9. Spatial distribution of road network sections with an above-average increase in traffic load for business trips due to a flood under a given scenario in Poland in 2019

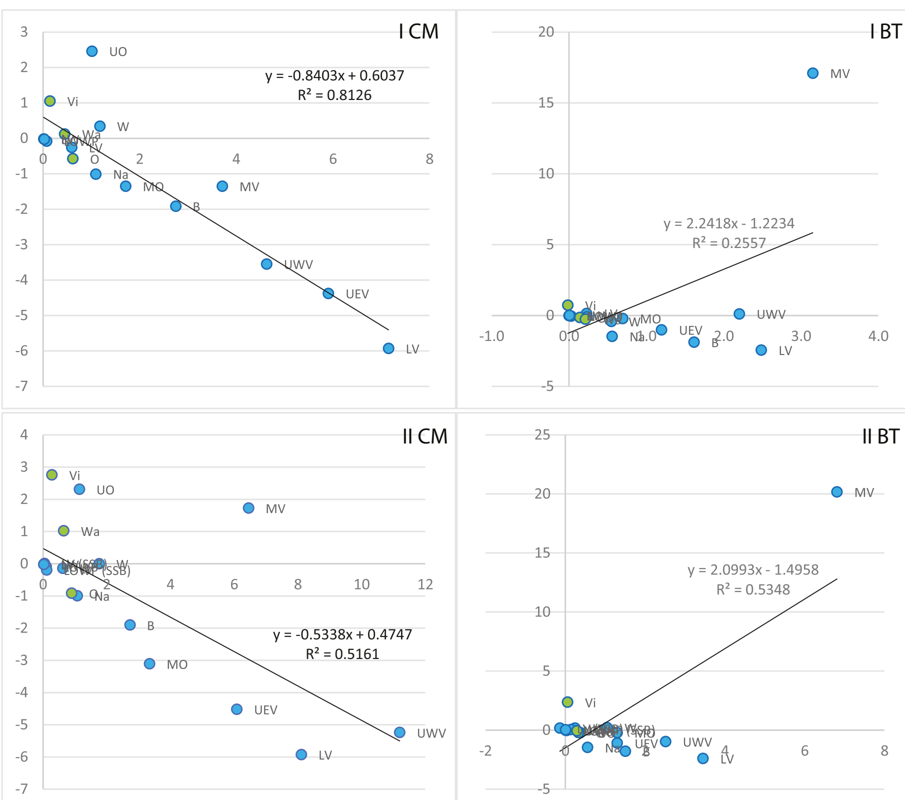
Source: own elaboration

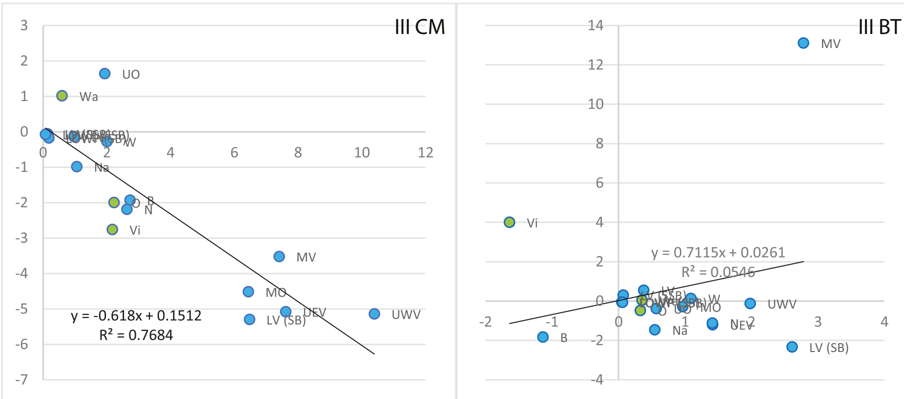
A considerable number of the regularities which characterise the distribution of road network sections with an above-average increase in commuter traffic load following a flood also occur when mobility stems from the necessity to conduct business trips. These concentrate particularly around Warsaw, or more generally on the road network within Masovian Province, on a spatial scale far beyond that of other agglomerations.

Alterations to travel routes and reductions in the number of commuter journeys and business trips proportional to the percentage of the residents of the transport region who live within flood hazard areas (against the total population) cause changes in vehicle-kilometres. For commuting to work, the maximum observed increase when compared to the "normal" situation amounted to over 11% for a 100-year flood in the water region of the Upper Western Vistula. A marginally smaller rise (10.39%) – due to higher drops in mobility – accompanied a complete breach of stopbanks there. For the water region of the Lower Vistula, a 10-year flood produces the largest relative increases in the number of vehicle-kilometres (7.14%). By comparison, the studies conducted by the Central Statistical Office (2015) show that 6.1% of the total number of vehicle-kilometres for passenger cars used to commute in Poland applies to trips within a 5-kilometre zone. These increases can be juxtaposed against the 10.7% of vehicle-kilometres observed for passenger cars used for travelling to work, but when the commuting distance is between 51 and 100 kilometres.

For business trips, the increases in vehicle-kilometres are generally lower, and there may even be some small drops (max. –1.64%). Regardless of the flood probability, however, this travel motivation shows the highest rises when accompanying a flood in the water region of the Middle Vistula. A 10-year flood may increase the volume of vehicle-kilometres by nearly 3.2% compared to "normal" circumstances there, which is the same value as the percentage of the total volume of vehicle-kilometres recorded for passenger cars used for business trips in Poland within the 6 to 10 km zone. On the other hand, the increase following a breach of stopbanks (2.78%) can be compared to the percentage of the total volume of vehicle-kilometres for passenger cars used for business trips, but only for those that are not shorter than 500 km. The largest increase in vehicle-kilometres (7%) is recorded for floods that have a probability of occurrence of once in a hundred years.

The relative changes in the number of vehicle-kilometres for the two travel motivations (commuting and business trips) and for the individual flood scenarios were juxtaposed with the Road Network Load Dispersion index (RNLD), which is the ratio of the standard deviation in traffic volumes observed on individual segments of the road network to the quotient of the total number of vehicle-kilometres and vehicles. By calculating the value of the index on the basis of the variables that describe the individual flood scenarios and the "normal" situation, it is possible to determine the magnitude and the reverse orientation of its change vector (Figure 8.10).





horizontal axis – change in the volume of vehicle-kilometres against the "normal" situation [%], vertical axis – relative change in the RNLD index [%]

Figure 8.10. Correlation between changes in the volume of vehicle-kilometres accompanying a flood in the different scenarios[11] and the corresponding changes in the differentiation of road network load for commuting (CM) and business trips (BT) in Poland in 2019

Source: own elaboration

A flood in the water region of the Upper Oder deserves closer scrutiny for commuter traffic. Despite the relatively small increases in the number of vehicle-kilometres that accompany a flood in this region, the volume of vehicle traffic on the national road network shows more diverse values, irrespective of the analysed flood probability. This is the consequence of the co-occurrence of a small reduction in the number of trips and high baseline values of traffic volumes within the network when this water region is affected by flooding. In most other scenarios, the drop in maximum traffic volumes on the network (despite local increases in vehicle numbers) contributes to a decrease in the total volume of vehicle-kilometres. When minimum values in areas outside those directly impacted by floods are kept at the baseline level, this translates into drops in the distribution of the road network load at the national scale. As regards business trips, it is

[11] I – 10% probability, II – a fluvial or a coastal flood (C) of 1% probability, III – a breach of stopbanks (SB) and a breach of the protective structure of the service strip (SSB); water regions: LV – the Lower Vistula, Na – the Narew, MV – the Middle Vistula, B – the Bug, UWV – the Upper Western Vistula, UEV – the Upper Eastern Vistula, LV – the Little Vistula, LOWP – the Lower Oder and the coastal strip of West Pomerania, N – the Noteć, W – the Warta, MO – the Middle Oder, UO – the Upper Oder, LW – the Łyna and the Węgorapa; main rivers (green dots): Vi – the Vistula, O – the Oder, Wa – the Warta.

worth mentioning the water region of the Middle Vistula, where floods – besides the highest increments in the number of vehicle-kilometres – are accompanied by the greatest increase in the distribution of observed vehicle traffic volumes.

The analysis of the effects of flooding for passenger road transport on road network load also took into account their spatial scope. Studying the magnitude with which changes in road infrastructure affect its surroundings poses a challenge, if only because it is difficult to specify the boundaries of the study area. A number of approaches are used, including analyses based on administrative borders (Ortega et al. 2012), a range of isolines (Holl 2004) or a combination of both (Stępniak and Rosik 2013). In the study presented here, two solutions were employed. The administrative division was applied by calculating the ratio of the number of municipalities where there were changes in the road network load accompanying commuting and business trips to the number of municipalities affected in a given flood scenario (Tables 8.1 and 8.2).

Table 8.1. Ratio of the number of municipalities affected by changes in road network load for commuter traffic to the total number of municipalities affected by flooding in a given scenario in Poland in 2019

	Flood scenario				
Water region	**10%**	**1%**	**1%C**	**SSB**	**SB**
the Bug	3.18	3.14	–	–	3.24
the Lower Vistula	2.06	2.11	2.71	2.66	2.09
the Upper Eastern Vistula	2.54	2.52	–	–	2.48
the Upper Western Vistula	2.18	2.69	–	–	2.86
the Little Vistula	3.89	4.06	–	–	4.11
the Narew	2.78	2.91	–	–	2.91
the Middle Vistula	2.65	2.63	–	–	2.86
the Lower Oder and the coastal strip of West Pomerania	1.40	2.00	1.76	1.77	1.96
the Upper Oder	2.11	2.42	–	–	2.47
the Noteć	0.43	0.96	–	–	4.04
the Middle Oder	1.39	1.66	–	–	1.83
the Warta	2.21	2.43	–	–	2.59
the Łyna and the Węgorapa	1.50	2.10	–	–	–
main river	**10%**	**1%**	**1%C**	**SSB**	**SB**
the Vistula	2.21	3.32	–	–	4.43
the Oder	2.64	3.43	–	–	4.14
the Warta	2.86	4.00	–	–	4.48

Source: own elaboration.

Table 8.2. Ratio of the number of municipalities affected by changes in road network load for business trips to the total number of municipalities affected by flooding in a given scenario in Poland in 2019

	Flood scenario				
Water region	**10%**	**1%**	**1%C**	**SSB**	**SB**
the Bug	8.15	7.92	–	–	8.28
the Lower Vistula	4.90	4.89	8.06	10.25	5.12
the Upper Eastern Vistula	6.58	6.33	–	–	6.60
the Upper Western Vistula	6.28	6.35	–	–	7.32
the Little Vistula	11.77	12.51	–	–	12.86
the Narew	9.18	9.00	–	–	9.13
the Middle Vistula	7.01	6.98	–	–	8.12
the Lower Oder and the coastal strip of West Pomerania	5.15	5.62	6.20	6.85	5.63
the Upper Oder	3.68	7.51	–	–	8.55
the Noteć	0.25	1.71	–	–	12.45
the Middle Oder	2.84	3.39	–	–	4.35
the Warta	5.72	6.18	–	–	6.50
the Łyna and the Węgorapa	11.50	13.10	–	–	–
main river	**10%**	**1%**	**1%C**	**SSB**	**SB**
the Vistula	8.12	9.19	–	–	10.62
the Oder	7.64	9.55	–	–	12.42
the Warta	10.94	11.36	–	–	12.99

Source: own elaboration.

For both commuting and business trips, the highest average quotient is observed in flood scenarios with a complete breach of stopbanks. The most varied results are found for commuting, while for business trips they are the most homogeneous. The second solution was based on the determination of the ratio of the spatial extent of changes in road network load accompanying the two trip motivations to the spatial extent of exclusions of road network sections due to flooding in a given scenario (Tables 8.3 and 8.4). For different water regions, road sections were determined where there were changes in traffic volumes in different flood scenarios. Next, these sections were grouped and inscribed into the smallest possible convex polygons that would cover them all, for a given water region and flood scenario.

Table 8.3. Ratio of the spatial scope of changes in road network load for commuting to work to the spatial scope of exclusions of road network sections due to flooding in a given scenario in Poland in 2019

	Flood scenario				
Water region	10%	1%	1%C	SSB	SB
the Bug	1.95	1.95	–	–	1.95
the Lower Vistula	1.81	1.96	3.43	2.76	2.14
the Upper Eastern Vistula	2.74	2.82	–	–	2.77
the Upper Western Vistula	1.81	2.58	–	–	2.82
the Little Vistula	8.15	8.04	–	–	12.51
the Narew	2.99	2.95	–	–	2.95
the Middle Vistula	2.61	2.63	–	–	2.61
the Lower Oder and the coastal strip of West Pomerania	1.26	2.67	3.35	8.18	2.65
the Upper Oder	2.67	2.87	–	–	2.85
the Noteć	3.45	2.57	–	–	3.00
the Middle Oder	1.33	1.44	–	–	1.64
the Warta	2.29	2.52	–	–	2.54
the Łyna and the Węgorapa	3.07	3.07	–	–	–
main river	**10%**	**1%**	**1%C**	**SSB**	**SB**
the Vistula	1.63	2.09	–	–	2.33
the Oder	2.58	3.04	–	–	2.70
the Warta	2.64	3.05	–	–	3.25

Source: own elaboration.

Table 8.4. Ratio of the spatial scope of changes in road network load for business travel to the spatial scope of exclusions of road network sections due to flooding in a given scenario in Poland in 2019

	Flood scenario				
Water region	10%	1%	1%C	SSB	SB
the Bug	6.45	7.10	–	–	7.23
the Lower Vistula	5.38	5.43	11.36	11.89	5.90
the Upper Eastern Vistula	8.23	8.09	–	–	9.74
the Upper Western Vistula	7.94	7.38	–	–	10.14
the Little Vistula	68.98	67.47	–	–	70.85
the Narew	11.50	11.35	–	–	12.96
the Middle Vistula	5.44	5.51	–	–	6.29
the Lower Oder and the coastal strip of West Pomerania	5.08	4.97	9.95	34.13	5.01
the Upper Oder	13.77	16.79	–	–	17.44
the Noteć	3.36	4.25	–	–	11.58
the Middle Oder	3.66	4.34	–	–	5.21
the Warta	4.80	5.29	–	–	5.79
the Łyna and the Węgorapa	15.00	15.02	–	–	–
main river	**10%**	**1%**	**1%C**	**SSB**	**SB**
the Vistula	3.09	3.17	–	–	3.49
the Oder	7.79	8.24	–	–	7.87
the Warta	5.71	5.75	–	–	7.37

Source: own elaboration.

Under this approach, a complete breach of stopbanks also returns the highest average quotient values, however, in contrast to the previous approach, here the greatest differentiation of results was recorded for business trips. The observed regional changeability in how the transport system responds to floods (examined only from the spatial perspective) does not only confirm how complex the nature of the system itself is, but it also proves what a challenge it is to create an effective infrastructural investment policy (Koziarski 2018). This is due to the fact that – besides meeting the current demand for transport services – it should also take into account the objectives of regional strategy, as stressed by Komornicki (2019).

9

CONCLUSIONS AND RECOMMENDATIONS

9.1. Conclusions and guidelines for further research

The main purpose of the study presented herein was to assess the vulnerability of the road transport in Poland by identifying the nature and magnitude of changes in transport accessibility, and changes in the load of the passenger road traffic on the network in the event of a flood in various probability scenarios. This main purpose has been achieved through the implementation of a series of detailed objectives that are cognitive, methodological, and applicational in nature.

The cognitive objectives included identification of conditions that determine the operation and development of road networks in flood hazard areas. The completion of this goal made it possible to develop a methodology for determining segments of the road network that would become inaccessible during a flood, which later allowed the author to accomplish the key objectives that involved determining the nature and scale of flood-related changes in temporal accessibility (isochronous, cumulative, and potential), and identification of the nature of changes in traffic flow volumes (related to obligatory motivations) due to flood-related closures of network sections and reduction of traffic-generating potentials. Eventually, it was possible to formulate recommendations for transport and spatial policies of areas at risk of flooding, which was a major applicational objective of the study.

As regards methodological objectives, models of the road network and vehicle traffic speeds in Poland were successfully constructed, offering a resolution that allowed for intra-municipal analyses to be performed. The high resolution made it possible to obtain results that captured even local flood-related changes within the transport system. Another methodological (but also applicational) objective successfully completed was the development of a software application to assess the process of demand distribution across the transport system network whose returned results made it possible to effectively analyse and visualise the impact of changes in the distribution of traffic on the network that accompany non-typical events.

A review of non-typical events that may impact the road transport in Poland shows that the vast majority involve two major types of interaction: water – road infrastructure, and water – vehicle. Even though it is difficult to determine all effects of these interactions, some consequences have already been thoroughly scrutinised by other branches of science. A flood is an example of water-related impact that puts the road infrastructure and its users to a particularly difficult test. The many historical reports (especially when there is an unfortunate coincidence of such factors as the flood hazard itself, and the scale of exposure, and vulnerability) show the broad spectrum of effects that floods may have on the transport system.

The said historical reports, together with a number of studies into the matter, confirm that the appearance of the first signs of the disaster or its actual occurrence may induce people to flee, thereby substantially increasing their mobility. A review of the research results and the various evacuation guidelines in transport management indicate that the optimisation of evacuation procedures poses a challenge in both theoretical and practical deliberations for both the correlation between journeys due to evacuation and the mobility that results from "regular" trip motivators. For both of the above, the results of their mutual influence may bring effects as varied as are the circumstances in which these trips are taken. The inconsistency of the tools implemented to optimise the evacuation process, the current state of the transport system, combined with the changeability of the threat itself and, above all, the variety of users and their different reactions to the danger, reveal how invaluable it is to take into account evacuation as a factor impacting road transport. At the same time, it is imperative to take into consideration local conditions and the local scale of spatial analysis in order to return realistic results.

Analysis of floods in Poland shows that they cause the greatest damage in the south (in the basins of the Upper Oder, the Middle Oder, and the Upper Vistula), which is reflected in the consequences for the road network and the resulting perturbations for the national system of road transport as a whole. The study into individual features of the natural environment and elements of land use that are at risk of flooding, expanded with research on the distribution of the population, made it possible to determine the principal conditions that impact the operation and development of the road network in the said territories. It is key that the legal and administrative regulations that accompany land use in flood hazard areas should resist change, even when the economic situation adds pressure to do so. Constantly changing the rules governing land use in these areas, even if done in good faith, impedes the expected positive effects since each change includes a transition period, which brings an element of insecurity and may lead to malpractices. Such legal changes also create problems for road networks as they can be spatially and substantively inconsistent. A local spatial policy, aimed at protecting floodplains and soundly conducted by a given municipality, will still be doomed to failure if the neighbouring authorities refuse to adopt such a plan perceiving it as an obstacle to regional development. One should aim at a state of affairs where no measures are taken to compromise the self-governance of local communities regarding the management of their own flood hazard areas. Where such communities willingly and actively participate in sustainable use and land development it will result in a decrease in their traffic-generating potential. Naturally, this requires raising both social awareness and environmental responsibility.

A review of source materials on the principles of construction and the use of the road infrastructure in flood hazard areas reveals a wide spectrum of regulations and good practices, the implementation of which is to ensure that the road infrastructure has the highest possible level of robustness to the damaging effects of floodwaters. The number of regulations, combined with the broad range of discussed threads shows that the significance of this factor for the appropriate operation of road transport has already been thoroughly considered in the realm of design and construction. The abundant documentation regulating the management of the road transport system in emergency situations proves that even the most earnest obedience to the guidelines cannot guarantee the sufficient robustness of those network segments exposed to flooding. Recognising the danger that non-typical events pose for the stability of the state's infrastructure, decision-makers need to regularly re-evaluate the strategic and operational guidelines, for which the results obtained in this monograph will provide indispensable diagnostic material to improve the security of the road transport system, including strategic and operational documentation. The method developed for assessing the impact of flood risk on road transport allows for the capture of flood hazards of extremely low probability but with catastrophic effects. Identification of those sections of the road network where disturbance or destruction would have the worst consequences for transport accessibility and road network load allows the bodies involved in managing critical infrastructure (operators) to prepare and implement plans to protect critical infrastructure once they are more precisely adjusted to the modelled scenarios. This also enables them to manage the available reserve resources more effectively. The conducted simulations facilitate a more efficient spatiotemporal distribution of the means and bodies that ensure safety and keep road infrastructure operational until it is fully recovered. The results returned in the monograph will also make it easier to raise the standards of management of critical infrastructure. Data on the exact location of those areas that are at elevated risk of reduced accessibility allows for prior measures to be taken that will guarantee that high accessibility of the road transport infrastructure is sustained at all times. The ability to recognise network segments that may be flooded or possibly "cut off," as well as those sections that will take and distribute traffic from the closed roads makes it possible to satisfy the demand for reliability in the context of the substitutability of individual elements of the network. What is more, the ability to identify the critical constituents of the network (especially those both critical and at risk) renders it significantly easier to maintain reliability when it comes to both interim and planned repairs and their scheduling.

None of the aforesaid support for infrastructure management, or even the road transport system as such, would be workable without identification of the locations where the exposure to hazard and infrastructural vulnerability is so unfavourable that the local infrastructure would be taken out of operation in the event of a flood. Development of a procedure to identify road sections at risk of inundation during a flood of a high and medium probability of occurrence or as a result of a complete breach of stopbanks or protective structures of the service strip posed a formidable challenge even in its conceptual stage, since it involved working with massive sets of data – data which can be diverse in terms of its spatial up-to-datedness. The assessment of data completeness and validity performed during the transition from the conceptual to operational stage revealed the need to conduct an additional process of a detailed verification of both existing road engineering structures and new developments. This required the acquisition of extremely large source material from institutions involved in the implementation of investments in road infrastructure. The material also varies depending on the territory it refers to, but – in this case – diversity relates primarily to the material form and volume of records. Nevertheless, with time and effort, it was possible to determine those sections at risk in the road network in Poland. The difficulties encountered in the analysis and interpretation of provisions within the collective documentation on investments in road infrastructure justify the advocacy for greater unification of the material describing investments compiled by the various bodies at different levels of territorial administration. In view of the inconveniences in accessing and analysing the design and construction documents, easier access to cross-referenced records would be a considerable facilitation.

As regards the said data and documentation, it must be stressed that there are substantial shortcomings and inaccuracies in the descriptions of even the most basic technical parameters of the civil engineering structures (bridges, culverts, etc.) that are listed in open-access vector databases. If one considers the strategic importance of such facilities for national defence or civil safety, it only feels reasonable to propose the improvement of the existing databases and the development of new ones which must contain parameters that ought to be freely available without compromising national security. Besides simplifying access to data, it would also result in the standardisation of records, which are currently spread across numerous departments and differ in up-to-datedness and availability. More extensive use of data on the properties of civil engineering structures would also make it possible to capture in greater detail the differences in their ability to “react” to hazards during the phase when road network models are being built for individual flooding scenarios.

Another important aspect for road transport studies would be access to more detailed data on floodwater levels for the (currently applied) initial range of up to 50 cm. A review of research papers indicates that even a difference of only a few centimetres may bring entirely different consequences for the road network and the trips made thereon. Although threshold values remain a disputable issue, and there is no consensus regarding the methodology applied, this contribution to the scientific debate is still believed to have been a valuable experience. If one takes into account the size of resources (data, computing power, etc.) necessary to model floodwater levels, the implementation of just one extra class range (e.g., up to 25 cm) would be a modification that could bring the enormous potential of additional research fields.

Further studies could also focus on the resilience of the transport system to changeability of floods over time. This refers to both movement of any floodwaves and the aftermath of flooding, so the period when it becomes possible to initiate actions to restore the road network to its previous state. This would pave the way for time-dependant analysis of journey shifts. Alas, data on the spatiotemporal dynamics of the phenomenon – at a scale applied in this study – remains unavailable, which made it impossible to incorporate it in this monograph. A valuable supplement to the presented model-based approach would also be to incorporate data not only on the changes in people's travel behaviour during the non-typical event in question, but also in the period preceding the actual flooding and its aftermath. Unfortunately, this is an extremely difficult task since the possibility of conducting real-time analyses is conditioned by the occurrence of floods. It is also limited by their high dynamics and by the fact that residents in distress may be quite reluctant to participate in any kind of social science research. Were it possible, however, it would satisfy the need for a greater assessment of the impact of human factors in such analyses, enabling the researcher to determine more accurately how flexible the road network is to demand change, distance decay, and modal shift which would characterise the emergency situation.

Further studies could also focus on other trip motivations, or even the application of a multi-motivation traffic model, since commuter traffic and business trips are just part (even if significant) of the total volume of traffic flows that accompany a number of motivations, and, therefore, it is impossible to draw comprehensive conclusions on congestion and the resultant drops in travel speeds within the network solely on the basis of these two motivations. For that reason, the study presented herein uses a model that makes these speeds more realistic, which could also be used with variables typical for other trip motivations and lengths, making it possible to distribute traffic reflecting the individual motivations in vehicle flows within the road network. What may seem unjustified is the incorporation of international trips and freight traffic, since many studies show that the majority of the road infrastructure used for these purposes is directly unaffected by floodwaters. However, the issue of indirect impact could still be researched, including congestion caused by extra traffic (e.g., users who take detours to avoid inundated areas while commuting to work) that appears on the roads also used by freight traffic.

The ability to recognise flood-related effects on the road network was merely a base for determining how it can impact the network's usability. This task was performed by means of a traffic speed model and the implementation of methods to assess changes in transport accessibility and road network load. The approach proposed herein to calculate vehicle speeds for individual segments of the high-resolution network (segments that differ greatly in terms of free-flow traffic) served its purpose. The initial assumptions of the model and its later calibration made it possible to develop a research tool that encompasses a broad spatial spectrum, with a high resolution of the road network model, combined with an acceptable degree of discrepancy in the returned results when juxtaposed against the applied calibration benchmark. This does not, however, change the fact that – despite the great efforts to make the model as flexible as possible in adjusting speeds to trip motivations – the approach may still be perceived as being too "rigid," especially for non-typical, simulated circumstances. A solution to this problem might be the application of traffic models and the data on traffic speed that such models return. While it seems feasible at a local or even regional scale (as long as the high resolution of the network model is maintained), it would still be extremely difficult to conduct on a greater scale.

Another benefit of combining analyses of changes in transport accessibility with simulative traffic models was the possibility to determine the fluctuations of mobility that follow disturbances to the integrity of the road network. The study presented here employs detailed data on the population within flood hazard areas when analysing accessibility and traffic density. Although this approach renders the scale of the assumed reductions of potentials more realistic, further improvements to the solution are still possible. Besides the data on resident numbers in areas at risk of flooding, it would also be advisable to inventory all other traffic generators, and to define the degree of traffic reduction that would stem from their inoperability in the event of a flood. Such detailed analyses also seem feasible only at a local scale, similarly to any attempts to calibrate a model that is to reflect distribution of flood-related traffic. Due to the highly dynamic nature of floods and the resultant problems with determining the shortest alternative routes, one could also consider applying an approach to traffic distribution within the transport network during a flood that is not based on situations which are deterministic from the user's perspective.

All the aforesaid results of the detailed cognitive and methodological goals of the monograph made it possible to achieve its major purpose – to determine the vulnerability of the passenger road transport in Poland through recognition of the nature and scale of changes in transport accessibility, and changes in the load of traffic on the road network. For both of the above, simulations were conducted for five different flooding scenarios, with spatial diversity encompassing individual water regions and additional variants for the three main rivers in Poland. The analyses revealed that, when it comes to reduced transport accessibility and operability of the road network, the road transport system shows spatially differentiated vulnerability to non-typical events. This vulnerability manifests itself both with regard to the transport component and land use (demographic component). Moreover, the returned results reveal the magnitude of disturbance to the basic levels of accessibility and traffic density, determined by the trip lengths and motivations.

Regardless of the length of the trips under study, a fluvial flood may be particularly disruptive for transport accessibility in the northern territories of Masovian Province and considerable parts of provinces in eastern Poland. Other regions that are characterised by a low basic level of accessibility and its substantial reduction due to flooding include the south of Lesser Poland, northern Greater Poland, Silesian Lowland, Sudeten Foothills, and the Lubusz Lake District. Even though all scenarios show that there are no substantial drops in accessibility for a fluvial flood in West Pomerania, this region – together with Pomerania and Warmia-Masuria – remains vulnerable to above-average drops in accessibility due to coastal flooding. However, it must be stated that the reductions of accessibility recorded for these flooding scenarios took relatively low percentage values. The poles of the highest basic values of accessibility that can be struck by particularly significant flood-related drops in accessibility include: municipalities to the north and northwest of Warsaw, areas in the vicinity of Bydgoszcz (for long trips), and areas along the A4 motorway between Wrocław and Opole, and Kraków and Rzeszów. As for commuting, particularly high increases in vehicle numbers are usually recorded on network segments adjacent to large urban agglomerations. Analyses show that the road network is often characterised by such a high number of optional travel routes that, although the inundation of one section may force users to look for a detour, they are not inclined to abandon their travel plans. This (usually local, limited and spatially diverted) traffic will sooner or later burden, in a cumulative manner, other network segments that lead directly to areas with a high density of workplaces. A considerable number of the regularities which characterise the distribution of road network sections with an above-average increase in commuter traffic load following a flood also occur when mobility stems from the necessity to conduct business trips. These concentrate particularly around Warsaw, or more generally on the road network within Masovian Province, on a spatial scale far beyond that of other agglomerations.

In general, floods that affect large areas are accompanied by more extreme drops in transport accessibility, putting a significantly greater strain (a considerable increase in vehicle-kilometres) on the transport system. However, the inhomogeneity of the road network and the diverse dispersion of potential within flood hazard areas means this correlation is not directly proportional. Moreover, it is difficult to find a relationship of this kind between the range of the direct impact of floodwaters on road infrastructure and the nationwide consequences for the road transport system as a whole. Nonetheless, it is still possible to identify the water regions where a flood would have the most severe impact on the equilibrium of the road transport system, thus greatly polarising accessibility. These include the water regions of the Middle Oder, the Upper Western Vistula, the Middle Vistula, and the Lower Vistula. Although these substantially exposed sections possess infrastructure crucial for the entire national system of road transport, one should be aware that current major investments and developments in road infrastructure will certainly mitigate the possible adverse effects for the road network users reported in this study.

The vastness of the derived research material, its multiple threads, together with the scope for possible further studies demonstrate the large cognitive potential behind the subject of how non-typical events (here: floods) impact road transport. At the same time, it must be stated that due to the complexity of the matter, it is impossible to avoid the implementation of certain simplifying assumptions or limitations, the awareness of which must accompany the process of interpreting the results.

9.2. Recommendations to reduce vulnerability of road network to flooding

Measures to reduce the vulnerability of road transport to floods should primarily be taken with regard to three spheres: road infrastructure and its management, road network users, and other forms of land use and development within flood hazard areas.

As for road infrastructure and its management, there are significant infrastructural investments and developments which are being (reasonably systematically) implemented and that will fulfil nationwide transport policies. It is crucial that these developments are completed, as they will ensure the highest possible level of basic transport accessibility and, more importantly, level the situation across the country spatially, which is also of great importance when one considers disruptions caused by floods and other non-typical events. Elimination of those highly exposed areas where residents have no free and convenient access to locations with high development potential will reduce the combined effects of existing low levels of basic accessibility and its substantial reductions due to an emergency situation.

Besides the importance of completing these key developments, it is also imperative to approach the investment policy in a manner adjusted to the needs of local road transport systems. When one considers how differently they were affected by the simulated hazards, it becomes obvious that a clearly-deliberated allocation of investment funds is a necessity, not only for current infrastructural needs, but – primarily – with regard to shaping current and future mobility. For some local networks, all that is needed is to renovate civil engineering structures, while others may have to rebuild substantial parts of their road network to take vehicle traffic that they are presently incapable of serving even in "normal" circumstances. Another important aspect is the scheduling of such measures to avoid undue disruption. It should not only take into account short-term priorities for a given investment, but also prognosed demographic changes, e.g., with regard to safety during evacuation. This is directly related to the second sphere mentioned above and takes the form of a mutuality, aimed at the compatibility between transport policy (or at least attempts to formulate it) and spatial policy, especially in territories at elevated risk of flooding, but also in areas where it is less likely. A separate challenge is to interlink the aforesaid key investments with local road networks. The "points of contact" of these two should be thoroughly analysed as they are particularly susceptible to various non-typical events, including floods.

The research results discussed in this monograph validate the need to analyse changes in transport accessibility at different spatial scales, especially for flood hazard areas. It is also necessary to conduct regular updates of studies in order to understand how the developments to the transport network; changes in the number, distribution, and strength of traffic-generating potentials; and the properties of the disaster itself (e.g., potential extents of the area affected) alter the situation. Accurate and detailed results from such analyses will allow those responsible to formulate and then implement procedures that govern transport and traffic flows at various spatial levels in a timely fashion. If improvements to traffic organisation are developed well in advance and combined with the appropriate channels of information for network users to be swiftly notified, it will take less time to bring the road transport system to a new level of equilibrium. It is the operators of the Intelligent Transport System who should be involved on a regional and national scale, as they have access to a range of tools to communicate with users, to send them warnings of disturbances within the road network and real-time recommendations on how to avoid them. On a regional and national scale, it gives operators the possibility to shape the desired transport behaviour in emergency situations. Besides the operating strategies and plans developed by transport administrators and organisers, at a local scale it is also advisable to use the returned results and research methodology to compile guidelines for residents of flood hazard areas and their immediate vicinity. At this level, if a flood directly and suddenly strikes a local community, a key role is attributed to well-drilled behaviour that would allow locals to choose the best route at the right time and using the most appropriate mode of transport. Not only would it mitigate the negative effects of flooding with regard to human health and life, but it would also increase the effectiveness of assistance provided by rescue services in terms of flood protection.

Given that floods cannot be totally avoided and, eventually, will affect the areas for which simulations were conducted in this study, it is imperative that measures are taken aimed at reducing the number of traffic generators in these areas. In this respect, it also seems necessary to develop and then strictly enforce coherent laws regulating land use in flood hazard areas.

A valuable supplement to the current management policy on flood hazard areas – also with operations and development of the road infrastructure in mind – would be to take into consideration the circumstances under which flood coverage may expand to incorporate territories the development of which had never before been conditioned by disaster-related factors. Global changes of the natural environment combined with local land use may lead to a situation where the extent of areas at a 1% probability of flood occurrence will expand to include territories that are currently at 0.2% risk of flooding. These lands, customarily perceived as completely safe, are characterised by an entirely different profile of land use, and their ongoing intensive development may result in increased costs from loss and damage to the road network in the event of a flood. Therefore, early recognition of a possible hazard (floods in particular) would make it possible to develop solutions that would not compromise the economic potential of such areas, while still taking into account the hazard itself. It would be useful to take into consideration historical data on past land use in areas where similar circumstances occurred, which may be useful in prognosing the future directions of changes and could signal the need for possible modifications of legislation to counteract undesired practices in such areas.

ANNEX

Table A.1. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a flood with a 10% probability of occurrence in the Vistula basin by water region in Poland in 2019 [%]

Water region	**Travel time [minutes]**	**Accumulated components**	**Size of settlement unit [population]**				
			up to 5,000	**5,001 to 20,000**	**20,001 to 50,000**	**50,001 to 100,000**	**over 100,000**
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Vistula	0–15	settlement units	–1.08	–1.18	–0.74	0.00	–2.63
		population	–1.26	–1.28	–1.11	0.00	–1.87
	15–30	settlement units	–1.71	–1.18	–1.48	–2.13	0.00
		population	–1.04	–1.03	–1.50	–1.85	0.00
	30–45	settlement units	1.87	2.36	1.48	0.00	0.00
		population	1.64	2.31	2.02	0.00	0.00
	45–60	settlement units	0.74	0.00	0.74	0.00	2.63
		population	0.50	0.00	0.60	0.00	1.87
the Narew	0–15	settlement units	–0.16	–0.24	–0.74	–2.13	0.00
		population	–0.10	–0.23	–0.65	–1.84	0.00
	15–30	settlement units	–0.40	0.24	0.74	2.13	0.00
		population	–0.34	0.23	0.65	1.84	0.00
	30–45	settlement units	0.07	0.00	0.00	0.00	0.00
		population	0.13	0.00	0.00	0.00	0.00
	45–60	settlement units	0.49	0.00	0.00	0.00	0.00
		population	0.32	0.00	0.00	0.00	0.00
the Middle Vistula	0–15	settlement units	–0.83	–0.71	–3.70	–4.26	–5.26
		population	–1.06	–1.16	–3.15	–3.67	–16.92
	15–30	settlement units	–1.77	0.24	2.96	2.13	2.63
		population	–0.91	0.58	2.45	2.03	1.09
	30–45	settlement units	1.19	0.47	0.00	2.13	0.00
		population	1.07	0.57	0.00	1.64	0.00
	45–60	settlement units	1.22	0.00	0.74	0.00	2.63
		population	0.76	0.00	0.70	0.00	15.83

Table A.1 (cont.)

1	2	3	4	5	6	7	8
the Bug	0–15	settlement units	–0.26	–0.24	–1.48	0.00	–2.63
		population	–0.34	–0.43	–1.13	0.00	–3.24
	15–30	settlement units	–1.09	–0.47	0.74	0.00	2.63
		population	–1.04	–0.58	0.65	0.00	3.24
	30–45	settlement units	0.48	0.47	0.00	0.00	0.00
		population	0.59	0.58	0.00	0.00	0.00
	45–60	settlement units	0.53	0.00	0.74	0.00	0.00
		population	0.49	0.00	0.48	0.00	0.00
the Upper Western Vistula	0–15	settlement units	–0.23	–0.47	–0.74	0.00	0.00
		population	–0.92	–0.35	–0.79	0.00	0.00
	15–30	settlement units	–0.73	–1.18	0.00	0.00	0.00
		population	–1.73	–0.77	0.00	0.00	0.00
	30–45	settlement units	0.35	0.71	0.00	0.00	0.00
		population	0.93	0.44	0.00	0.00	0.00
	45–60	settlement units	0.27	–0.24	0.00	0.00	0.00
		population	0.58	–0.26	0.00	0.00	0.00
the Upper Eastern Vistula	0–15	settlement units	–0.24	–0.71	–0.74	0.00	0.00
		population	–1.03	–0.49	–1.12	0.00	0.00
	15–30	settlement units	–0.64	0.24	0.00	0.00	0.00
		population	–1.25	0.13	0.00	0.00	0.00
	30–45	settlement units	0.16	0.47	0.74	0.00	0.00
		population	0.86	0.36	1.12	0.00	0.00
	45–60	settlement units	0.44	0.00	0.00	0.00	0.00
		population	1.09	0.00	0.00	0.00	0.00
the Little Vistula	0–15	settlement units	–0.01	–0.24	–0.74	0.00	0.00
		population	–0.02	–0.19	–0.83	0.00	0.00
	15–30	settlement units	–0.01	0.00	0.74	0.00	0.00
		population	–0.08	–0.10	0.83	0.00	0.00
	30–45	settlement units	0.02	0.24	0.00	0.00	0.00
		population	0.10	0.29	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.2. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a flood with a 10% probability of occurrence in the Oder basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Oder and the coastal strip of West Pomerania	0–15	settlement units	–0.16	0.00	0.00	0.00	0.00
		population	–0.09	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.06	–0.24	0.00	0.00	0.00
		population	–0.06	–0.32	0.00	0.00	0.00
	30–45	settlement units	0.18	0.24	0.00	0.00	0.00
		population	0.11	0.32	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.01	0.00	0.00	0.00	0.00
the Noteć	0–15	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	15–30	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	30–45	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
the Warta	0–15	settlement units	–0.26	–0.71	–1.48	0.00	0.00
		population	–0.22	–0.86	–1.57	0.00	0.00
	15–30	settlement units	–0.64	–0.24	0.74	0.00	0.00
		population	–0.43	–0.10	0.54	0.00	0.00
	30–45	settlement units	0.56	0.94	0.74	0.00	0.00
		population	0.42	0.96	1.03	0.00	0.00
	45–60	settlement units	0.34	0.00	0.00	0.00	0.00
		population	0.23	0.00	0.00	0.00	0.00
the Middle Oder	0–15	settlement units	–0.42	–0.94	–3.70	–2.13	0.00
		population	–0.59	–1.08	–3.45	–2.52	0.00
	15–30	settlement units	–0.68	–0.71	0.74	2.13	0.00
		population	–0.54	–0.70	0.49	2.52	0.00
	30–45	settlement units	0.88	1.18	2.22	0.00	0.00
		population	0.89	1.12	2.48	0.00	0.00
	45–60	settlement units	0.19	0.00	0.74	0.00	0.00
		population	0.20	0.13	0.48	0.00	0.00

Table A.2 (cont.)

1	2	3	4	5	6	7	8
the Upper Oder	0–15	settlement units	–0.07	0.00	–0.74	0.00	0.00
		population	–0.11	0.00	–0.51	0.00	0.00
	15–30	settlement units	–0.08	0.00	0.00	0.00	0.00
		population	–0.13	0.00	–0.36	0.00	0.00
	30–45	settlement units	0.13	0.00	0.74	0.00	0.00
		population	0.20	0.00	0.86	0.00	0.00
	45–60	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.04	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.3. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a flood with a 10% probability of occurrence in the Pregolya basin in Poland in 2019 [%]

			Size of settlement unit [population]				
Water region	**Travel time [minutes]**	**Accumulated components**	**up to 5,000**	**5,001 to 20,000**	**20,001 to 50,000**	**50,001 to 100,000**	**over 100,000**
			relative changes [%]				
the Łyna and the Węgorapa	0–15	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	30–45	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.01	0.00	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.4. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a flood with a 10% probability of occurrence on the main rivers in Poland in 2019 [%]

River	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Vistula	0–15	settlement units	–0.03	0.00	0.00	0.00	–2.63
		population	–0.02	0.00	0.00	0.00	–1.87
	15–30	settlement units	–0.09	–0.24	0.00	0.00	2.63
		population	–0.09	–0.15	0.00	0.00	1.87
	30–45	settlement units	0.11	0.24	0.00	0.00	0.00
		population	0.09	0.15	0.00	0.00	0.00
	45–60	settlement units	0.02	0.00	0.00	0.00	0.00
		population	0.02	0.00	0.00	0.00	0.00
the Oder	0–15	settlement units	–0.10	0.00	0.00	0.00	0.00
		population	–0.16	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.30	–0.24	–0.74	0.00	0.00
		population	–0.32	–0.32	–0.86	0.00	0.00
	30–45	settlement units	0.28	0.00	0.74	0.00	0.00
		population	0.39	–0.07	0.86	0.00	0.00
	45–60	settlement units	0.10	0.24	0.00	0.00	0.00
		population	0.07	0.38	0.00	0.00	0.00
the Warta	0–15	settlement units	–0.11	0.00	–1.48	0.00	0.00
		population	–0.12	0.00	–1.57	0.00	0.00
	15–30	settlement units	–0.35	–0.47	0.74	0.00	0.00
		population	–0.21	–0.56	0.54	0.00	0.00
	30–45	settlement units	0.27	0.47	0.74	0.00	0.00
		population	0.24	0.56	1.03	0.00	0.00
	45–60	settlement units	0.18	0.00	0.00	0.00	0.00
		population	0.09	0.00	0.00	0.00	0.00

Source: own elaboration

Table A.5. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a (fluvial) flood with a 1% probability of occurrence in the Vistula basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Vistula	0–15	settlement units	–1.08	–1.18	–1.48	0.00	–2.63
		population	–1.26	–1.28	–1.76	0.00	–1.87
	15–30	settlement units	–1.74	–1.18	–0.74	–2.13	0.00
		population	–1.09	–1.03	–0.86	–1.85	0.00
	30–45	settlement units	1.87	2.36	1.48	0.00	0.00
		population	1.65	2.31	2.02	0.00	0.00
	45–60	settlement units	0.77	0.00	0.74	0.00	2.63
		population	0.53	0.00	0.60	0.00	1.87
the Narew	0–15	settlement units	–0.16	–0.24	–0.74	–2.13	0.00
		population	–0.11	–0.23	–0.65	–1.84	0.00
	15–30	settlement units	–0.43	0.24	0.74	2.13	0.00
		population	–0.35	0.23	0.65	1.84	0.00
	30–45	settlement units	–0.07	0.00	0.00	0.00	0.00
		population	0.07	0.00	0.00	0.00	0.00
	45–60	settlement units	0.66	0.00	0.00	0.00	0.00
		population	0.39	0.00	0.00	0.00	0.00
the Middle Vistula	0–15	settlement units	–0.88	–0.71	–3.70	–4.26	–5.26
		population	–1.12	–1.16	–3.15	–3.67	–16.92
	15–30	settlement units	–1.86	0.24	2.96	2.13	2.63
		population	–0.96	0.58	2.45	2.03	1.09
	30–45	settlement units	1.40	0.47	0.00	2.13	2.63
		population	1.19	0.57	0.00	1.64	15.83
	45–60	settlement units	1.14	0.00	0.74	0.00	0.00
		population	0.74	0.00	0.70	0.00	0.00
the Bug	0–15	settlement units	–0.28	–0.24	–0.74	0.00	–2.63
		population	–0.37	–0.43	–0.48	0.00	–3.24
	15–30	settlement units	–1.22	–0.71	0.00	0.00	2.63
		population	–1.14	–0.73	0.00	0.00	3.24
	30–45	settlement units	0.55	0.71	0.00	0.00	0.00
		population	0.66	0.73	0.00	0.00	0.00
	45–60	settlement units	0.47	0.00	0.74	0.00	0.00
		population	0.45	0.00	0.48	0.00	0.00

1	2	3	4	5	6	7	8
the Upper Western Vistula	0–15	settlement units	–0.25	–0.47	–0.74	0.00	0.00
		population	–0.96	–0.35	–0.79	0.00	0.00
	15–30	settlement units	–0.82	–1.18	0.00	0.00	0.00
		population	–1.92	–0.77	0.00	0.00	0.00
	30–45	settlement units	0.39	0.71	0.00	0.00	0.00
		population	1.06	0.44	0.00	0.00	0.00
	45–60	settlement units	0.32	–0.24	0.00	0.00	0.00
		population	0.63	–0.26	0.00	0.00	0.00
the Upper Eastern Vistula	0–15	settlement units	–0.24	–0.71	–0.74	0.00	0.00
		population	–1.03	–0.49	–1.12	0.00	0.00
	15–30	settlement units	–0.64	0.24	0.00	0.00	0.00
		population	–1.25	0.13	0.00	0.00	0.00
	30–45	settlement units	0.16	0.47	0.74	0.00	0.00
		population	0.86	0.36	1.12	0.00	0.00
	45–60	settlement units	0.44	0.00	0.00	0.00	0.00
		population	1.09	0.00	0.00	0.00	0.00
the Little Vistula	0–15	settlement units	–0.02	–0.24	–0.74	0.00	0.00
		population	–0.06	–0.19	–0.83	0.00	0.00
	15–30	settlement units	0.00	0.00	0.74	0.00	0.00
		population	–0.08	–0.10	0.83	0.00	0.00
	30–45	settlement units	0.03	0.24	0.00	0.00	0.00
		population	0.14	0.29	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.6. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a (fluvial) flood with a 1% probability of occurrence in the Oder basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	**5,001 to 20,000**	**20,001 to 50,000**	**50,001 to 100,000**	**over 100,000**
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Oder and the coastal strip of West Pomerania	0–15	settlement units	–0.19	0.00	0.00	0.00	0.00
		population	–0.12	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.08	–0.24	0.00	0.00	0.00
		population	–0.07	–0.32	0.00	0.00	0.00
	30–45	settlement units	0.23	0.24	0.00	0.00	0.00
		population	0.15	0.32	0.00	0.00	0.00
	45–60	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00

Table A.6 (cont.)

1	2	3	4	5	6	7	8
the Noteć	0–15	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.05	0.00	0.00	0.00	0.00
		population	–0.04	0.00	0.00	0.00	0.00
	30–45	settlement units	0.04	0.00	0.00	0.00	0.00
		population	0.03	0.00	0.00	0.00	0.00
	45–60	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.01	0.00	0.00	0.00	0.00
the Warta	0–15	settlement units	–0.26	–0.71	–1.48	0.00	0.00
		population	–0.22	–0.86	–1.57	0.00	0.00
	15–30	settlement units	–0.64	–0.24	0.74	0.00	0.00
		population	–0.43	–0.10	0.54	0.00	0.00
	30–45	settlement units	0.56	0.94	0.74	0.00	0.00
		population	0.42	0.96	1.03	0.00	0.00
	45–60	settlement units	0.34	0.00	0.00	0.00	0.00
		population	0.23	0.00	0.00	0.00	0.00
the Middle Oder	0–15	settlement units	–0.70	–1.18	–3.70	–4.26	0.00
		population	–1.06	–1.23	–3.45	–5.64	0.00
	15–30	settlement units	–1.01	–1.89	0.74	0.00	0.00
		population	–0.95	–1.90	0.49	0.00	0.00
	30–45	settlement units	0.91	1.42	1.48	2.13	0.00
		population	1.09	1.48	1.42	3.11	0.00
	45–60	settlement units	0.54	1.18	1.48	2.13	0.00
		population	0.54	1.26	1.54	2.52	0.00
the Upper Oder	0–15	settlement units	–0.12	–0.47	–0.74	0.00	0.00
		population	–0.22	–0.51	–0.51	0.00	0.00
	15–30	settlement units	–0.26	0.24	0.00	–2.13	0.00
		population	–0.45	0.13	–0.36	–1.69	0.00
	30–45	settlement units	0.30	0.00	0.74	2.13	0.00
		population	0.52	0.00	0.86	1.69	0.00
	45–60	settlement units	0.08	0.24	0.00	0.00	0.00
		population	0.15	0.38	0.00	0.00	0.00

Source: own elaboration

Table A.7. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a (fluvial) flood with a 1% probability of occurrence in the Pregolya basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Łyna and the Węgorapa	0–15	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	30–45	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.01	0.00	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.8. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a (fluvial) flood with a 1% probability of occurrence on the main rivers in Poland in 2019 [%]

River	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Vistula	0–15	settlement units	–0.09	0.00	–0.74	0.00	–5.26
		population	–0.10	0.00	–0.65	0.00	–2.96
	15–30	settlement units	–0.18	–0.47	0.74	–2.13	5.26
		population	–0.17	–0.39	0.65	–1.85	2.96
	30–45	settlement units	0.16	0.47	0.00	2.13	0.00
		population	0.20	0.39	0.00	1.85	0.00
	45–60	settlement units	0.11	0.00	0.00	0.00	0.00
		population	0.07	0.00	0.00	0.00	0.00
the Oder	0–15	settlement units	–0.17	–0.24	0.00	0.00	0.00
		population	–0.30	–0.38	0.00	0.00	0.00
	15–30	settlement units	–0.49	–0.24	–0.74	–2.13	0.00
		population	–0.52	–0.32	–0.86	–1.69	0.00
	30–45	settlement units	0.34	0.00	0.74	2.13	0.00
		population	0.51	–0.07	0.86	1.69	0.00
	45–60	settlement units	0.28	0.47	0.00	0.00	0.00
		population	0.28	0.77	0.00	0.00	0.00

Table A.8 (cont.)

1	2	3	4	5	6	7	8
the Warta	0–15	settlement units	–0.14	–0.47	–1.48	0.00	–2.63
		population	–0.17	–0.69	–1.57	0.00	–4.98
	15–30	settlement units	–0.42	–0.94	0.74	0.00	2.63
		population	–0.29	–0.74	0.54	0.00	4.98
	30–45	settlement units	0.38	1.42	0.74	0.00	0.00
		population	0.36	1.43	1.03	0.00	0.00
	45–60	settlement units	0.18	0.00	0.00	0.00	0.00
		population	0.10	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.9. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a (coastal) flood with a 1% probability of occurrence in the Vistula basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Vistula	0–15	settlement units	–0.05	–0.47	0.00	0.00	–2.63
		population	–0.06	–0.47	0.00	0.00	–4.26
	15–30	settlement units	–0.08	0.24	0.00	0.00	0.00
		population	–0.08	0.24	0.00	0.00	0.00
	30–45	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	–0.02	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.10. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a (coastal) flood with a 1% probability of occurrence in the Oder basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Oder and the coastal strip of West Pomerania	0–15	settlement units	–0.03	–0.24	0.00	0.00	–2.63
		population	–0.02	–0.15	0.00	0.00	–3.70
	15–30	settlement units	–0.02	0.24	0.00	0.00	2.63
		population	0.00	0.15	0.00	0.00	3.70
	30–45	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	45–60	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.11. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a complete breach of the protective structures of the service strip in the Vistula basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Vistula	0–15	settlement units	–0.17	–0.24	0.00	0.00	0.00
		population	–0.14	–0.23	0.00	0.00	0.00
	15–30	settlement units	–0.22	0.00	–0.74	–2.13	0.00
		population	–0.20	0.00	–0.91	–1.85	0.00
	30–45	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.12. Relative changes in the number of affected settlement units and the population residing there for 15-minute intervals of travel time to county seats due to a complete breach of the protective structures of the service strip in the Oder basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Oder and the coastal strip of West Pomerania	0–15	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	15–30	settlement units	–0.04	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–45	settlement units	0.05	0.00	0.00	0.00	0.00
		population	0.01	0.00	0.00	0.00	0.00
	45–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.13. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a flood with a 10% probability of occurrence in the Vistula basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Vistula	0–30	settlement units	–0.60	–1.18	–0.74	0.00	–2.63
		population	–0.81	–1.12	–0.65	0.00	–1.87
	30–60	settlement units	–2.14	–2.36	–2.22	–2.13	2.63
		population	–1.65	–2.41	–2.24	–1.85	1.87
	60–90	settlement units	–0.41	–0.24	0.00	–2.13	0.00
		population	–0.01	–0.42	–0.43	–2.33	0.00
	90–120	settlement units	2.00	2.59	2.96	2.13	0.00
		population	1.63	2.63	3.32	1.29	0.00
the Narew	0–30	settlement units	–0.05	–0.24	0.00	0.00	0.00
		population	–0.05	–0.36	0.00	0.00	0.00
	30–60	settlement units	–0.16	0.24	0.00	–2.13	0.00
		population	–0.07	0.36	0.00	–1.93	0.00
	60–90	settlement units	–0.93	–0.24	–0.74	2.13	0.00
		population	–0.55	–0.24	–0.52	1.93	0.00
	90–120	settlement units	0.06	0.24	0.00	0.00	0.00
		population	0.05	0.24	0.00	0.00	0.00
the Middle Vistula	0–30	settlement units	–0.26	–0.94	–0.74	–2.13	–2.63
		population	–0.59	–0.91	–0.97	–1.81	–15.83
	30–60	settlement units	–1.46	–0.47	–2.22	0.00	–2.63
		population	–0.74	–0.64	–1.56	0.16	–1.09
	60–90	settlement units	–1.83	0.00	1.48	–2.13	0.00
		population	–1.02	–0.04	0.81	–2.28	–0.10
	90–120	settlement units	2.56	0.47	0.74	2.13	5.26
		population	1.70	0.66	1.07	2.28	17.02
the Bug	0–30	settlement units	–0.45	–0.24	–2.22	0.00	–2.63
		population	–0.78	–0.16	–1.96	0.00	–3.24
	30–60	settlement units	–1.58	–0.94	0.00	–2.13	0.00
		population	–1.40	–1.32	–0.22	–2.06	0.00
	60–90	settlement units	–1.69	–0.71	0.74	–2.13	2.63
		population	–1.28	–1.29	0.97	–2.06	3.24
	90–120	settlement units	0.56	0.47	0.74	0.00	0.00
		population	0.68	1.02	0.73	0.25	0.00
the Upper Western Vistula	0–30	settlement units	–0.20	–0.47	0.00	0.00	0.00
		population	–0.40	–0.49	0.00	0.00	0.00
	30–60	settlement units	–0.77	–1.65	–0.74	0.00	0.00
		population	–1.21	–1.61	–0.93	0.00	0.00
	60–90	settlement units	0.18	0.00	–0.74	–2.13	0.00
		population	–0.65	0.35	–0.62	–2.64	0.00
	90–120	settlement units	0.32	0.71	0.74	0.00	0.00
		population	0.50	0.55	0.76	0.00	0.00

1	2	3	4	5	6	7	8
the Upper Eastern Vistula	0–30	settlement units	–0.10	–0.24	0.00	0.00	0.00
		population	–0.49	–0.15	0.00	0.00	0.00
	30–60	settlement units	–0.48	–2.12	–1.48	0.00	0.00
		population	–1.39	–1.70	–2.04	0.00	0.00
	60–90	settlement units	–0.65	1.42	–0.74	–2.13	0.00
		population	–0.85	1.11	–0.87	–2.01	0.00
	90–120	settlement units	0.09	0.71	1.48	0.00	0.00
		population	0.68	0.61	1.79	0.00	0.00
the Little Vistula	0–30	settlement units	0.00	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.12	–1.65	–0.74	0.00	–2.63
		population	–0.52	–1.30	–0.83	0.00	–1.65
	60–90	settlement units	0.04	0.94	0.74	0.00	2.63
		population	0.18	0.78	0.83	0.00	1.65
	90–120	settlement units	0.07	0.71	0.00	0.00	0.00
		population	0.34	0.52	0.00	0.00	0.00

Source: own elaboration.

Table A.14. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a flood with a 10% probability of occurrence in the Oder basin by water region in Poland in 2019 [%]

Water region	**Travel time [minutes]**	**Accumulated components**	**Size of settlement unit [population]**				
			up to 5,000	**5,001 to 20,000**	**20,001 to 50,000**	**50,001 to 100,000**	**over 100,000**
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Oder and the coastal strip of West Pomerania	0–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–60	settlement units	0.01	0.00	0.00	0.00	0.00
		population	–0.02	0.00	0.00	0.00	0.00
	60–90	settlement units	–0.03	–0.24	0.00	0.00	0.00
		population	–0.04	–0.36	0.00	0.00	0.00
	90–120	settlement units	–0.01	0.24	0.00	0.00	0.00
		population	0.03	0.36	0.00	0.00	0.00
the Noteć	0–30	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	30–60	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	60–90	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	90–120	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00

Table A.14 (cont.)

1	2	3	4	5	6	7	8
the Warta	0–30	settlement units	–0.08	–0.71	0.00	0.00	0.00
		population	–0.10	–0.64	0.00	0.00	0.00
	30–60	settlement units	–0.63	0.71	–1.48	–2.13	0.00
		population	–0.54	0.51	–1.61	–1.62	0.00
	60–90	settlement units	0.03	–0.24	1.48	2.13	0.00
		population	0.12	–0.03	1.61	1.62	0.00
	90–120	settlement units	0.68	0.24	0.00	0.00	0.00
		population	0.52	0.16	0.00	0.00	0.00
the Middle Oder	0–30	settlement units	–0.08	–0.24	0.00	0.00	0.00
		population	–0.08	–0.14	0.00	0.00	0.00
	30–60	settlement units	–0.48	–0.47	–1.48	0.00	0.00
		population	–0.59	–0.27	–1.92	0.00	0.00
	60–90	settlement units	0.24	–0.47	–0.74	0.00	0.00
		population	0.11	–0.47	0.18	0.00	0.00
	90–120	settlement units	0.26	0.71	2.22	0.00	0.00
		population	0.54	0.32	1.74	0.00	0.00
the Upper Oder	0–30	settlement units	–0.06	0.00	0.00	0.00	0.00
		population	–0.21	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.48	–0.24	–1.48	0.00	0.00
		population	–0.47	–0.14	–1.37	0.00	0.00
	60–90	settlement units	0.25	0.24	1.48	0.00	0.00
		population	0.34	0.14	1.37	0.00	0.00
	90–120	settlement units	0.29	0.00	0.00	0.00	0.00
		population	0.34	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.15. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a flood with a 10% probability of occurrence in the Pregolya basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Łyna and the Węgorapa	0–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.04	0.24	0.00	0.00	0.00
		population	–0.01	0.18	0.00	0.00	0.00
	60–90	settlement units	0.05	–0.24	0.00	0.00	0.00
		population	0.05	–0.18	0.00	0.00	0.00
	90–120	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.02	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.16. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a flood with a 10% probability of occurrence on the main rivers in Poland in 2019 [%]

River	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Vistula	0–30	settlement units	–0.08	0.00	0.00	0.00	0.00
		population	–0.04	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.07	0.00	0.00	0.00	0.00
		population	–0.10	0.03	0.00	0.00	0.00
	60–90	settlement units	–0.13	0.00	0.00	0.00	0.00
		population	0.00	–0.03	0.00	0.00	0.00
	90–120	settlement units	0.28	0.00	0.00	0.00	0.00
		population	0.15	0.00	0.00	0.00	0.00
the Oder	0–30	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.09	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.26	0.24	–0.74	0.00	0.00
		population	–0.19	0.28	–0.86	0.00	0.00
	60–90	settlement units	0.26	–0.24	0.74	0.00	0.00
		population	0.26	–0.28	0.86	0.00	0.00
	90–120	settlement units	0.03	0.00	0.00	0.00	0.00
		population	0.03	0.00	0.00	0.00	0.00
the Warta	0–30	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.03	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.25	0.24	–0.74	–2.13	0.00
		population	–0.31	0.18	–1.03	–1.62	0.00
	60–90	settlement units	0.04	–0.24	0.74	2.13	0.00
		population	0.16	–0.18	1.03	1.62	0.00
	90–120	settlement units	0.23	0.00	0.00	0.00	0.00
		population	0.17	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.17. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a (fluvial) flood with a 1% probability of occurrence in the Vistula basin by water region in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Vistula	0–30	settlement units	–0.63	–1.18	–0.74	0.00	–2.63
		population	–0.85	–1.12	–0.65	0.00	–1.87
	30–60	settlement units	–2.14	–2.36	–2.22	–2.13	2.63
		population	–1.63	–2.41	–2.24	–1.85	1.87
	60–90	settlement units	–0.38	–0.24	0.00	–2.13	0.00
		population	0.00	–0.42	–0.43	–2.33	0.00
	90–120	settlement units	2.00	2.59	2.96	2.13	0.00
		population	1.63	2.63	3.32	1.29	0.00
the Narew	0–30	settlement units	–0.05	–0.47	0.00	0.00	0.00
		population	–0.03	–0.60	0.00	0.00	0.00
	30–60	settlement units	–0.16	0.47	0.00	–2.13	0.00
		population	–0.08	0.60	0.00	–1.93	0.00
	60–90	settlement units	–1.05	–0.24	–0.74	2.13	0.00
		population	–0.60	–0.24	–0.52	1.93	0.00
	90–120	settlement units	0.04	0.24	0.00	0.00	0.00
		population	0.04	0.24	0.00	0.00	0.00
the Middle Vistula	0–30	settlement units	–0.26	–0.94	–0.74	–2.13	–2.63
		population	–0.60	–0.91	–0.97	–1.81	–15.83
	30–60	settlement units	–1.52	–0.47	–2.22	–2.13	–2.63
		population	–0.80	–0.64	–1.56	–1.49	–1.09
	60–90	settlement units	–2.01	0.00	1.48	0.00	0.00
		population	–1.17	–0.04	0.81	–0.64	–0.10
	90–120	settlement units	2.71	0.47	0.74	2.13	5.26
		population	1.85	0.66	1.07	2.28	17.02
the Bug	0–30	settlement units	–0.45	–0.24	–2.22	0.00	–2.63
		population	–0.78	–0.16	–1.96	0.00	–3.24
	30–60	settlement units	–1.62	–0.47	0.00	–2.13	0.00
		population	–1.39	–0.82	–0.22	–2.06	0.00
	60–90	settlement units	–1.69	–1.18	0.74	–2.13	2.63
		population	–1.31	–1.80	0.97	–2.06	3.24
	90–120	settlement units	0.55	0.47	0.74	0.00	0.00
		population	0.68	1.02	0.73	0.25	0.00
the Upper Western Vistula	0–30	settlement units	–0.20	–0.47	0.00	0.00	0.00
		population	–0.40	–0.49	0.00	0.00	0.00
	30–60	settlement units	–0.77	–1.65	–0.74	0.00	0.00
		population	–1.21	–1.61	–0.93	0.00	0.00
	60–90	settlement units	0.18	0.00	–0.74	–2.13	0.00
		population	–0.65	0.35	–0.62	–2.64	0.00
	90–120	settlement units	0.32	0.71	0.74	0.00	0.00
		population	0.50	0.55	0.76	0.00	0.00

1	2	3	4	5	6	7	8
the Upper Eastern Vistula	0–30	settlement units	–0.11	–0.47	0.00	0.00	0.00
		population	–0.59	–0.56	0.00	0.00	0.00
	30–60	settlement units	–0.65	–2.36	–1.48	0.00	0.00
		population	–2.17	–2.07	–2.04	0.00	0.00
	60–90	settlement units	–1.01	0.71	–1.48	–2.13	0.00
		population	–2.00	0.71	–1.79	–2.01	0.00
	90–120	settlement units	–0.09	0.00	0.74	0.00	0.00
		population	0.27	0.00	0.87	0.00	0.00
the Little Vistula	0–30	settlement units	–0.02	–0.24	0.00	0.00	0.00
		population	–0.03	–0.21	0.00	0.00	0.00
	30–60	settlement units	–0.09	–1.42	–0.74	0.00	–2.63
		population	–0.48	–1.09	–0.83	0.00	–1.65
	60–90	settlement units	0.03	0.94	0.74	0.00	2.63
		population	0.16	0.78	0.83	0.00	1.65
	90–120	settlement units	0.08	0.71	0.00	0.00	0.00
		population	0.34	0.52	0.00	0.00	0.00

Source: own elaboration.

Table A.18. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a (fluvial) flood with a 1% probability of occurrence in the Oder basin by water region in Poland in 2019 [%]

			Size of settlement unit [population]				
Water region	**Travel time [minutes]**	**Accumulated components**	**up to 5,000**	**5,001 to 20,000**	**20,001 to 50,000**	**50,001 to 100,000**	**over 100,000**
			relative changes [%]				
1	2	3	4	5	6	7	8
the Lower Oder and the coastal strip of West Pomerania	0–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.06	0.00	0.00	0.00	0.00
	60–90	settlement units	–0.01	–0.24	0.00	0.00	0.00
		population	–0.01	–0.36	0.00	0.00	0.00
	90–120	settlement units	0.00	0.24	0.00	0.00	0.00
		population	0.05	0.36	0.00	0.00	0.00
the Noteć	0–30	settlement units	–0.02	0.00	0.00	0.00	0.00
		population	–0.02	0.00	0.00	0.00	0.00
	30–60	settlement units	0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	60–90	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.02	0.00	0.00	0.00	0.00
	90–120	settlement units	0.01	0.00	0.00	0.00	0.00
		population	0.01	0.00	0.00	0.00	0.00

Table A.18 (cont.)

1	2	3	4	5	6	7	8
the Warta	0–30	settlement units	–0.09	–0.94	0.00	0.00	–2.63
		population	–0.17	–0.85	0.00	0.00	–4.98
	30–60	settlement units	–0.93	0.00	–1.48	–2.13	2.63
		population	–0.81	–0.17	–1.61	–1.62	4.98
	60–90	settlement units	–0.15	0.71	1.48	2.13	0.00
		population	0.12	0.86	1.61	1.62	0.00
	90–120	settlement units	1.18	0.24	0.00	0.00	0.00
		population	0.86	0.16	0.00	0.00	0.00
the Middle Oder	0–30	settlement units	–0.18	–0.24	–0.74	0.00	0.00
		population	–0.22	–0.14	–0.88	0.00	0.00
	30–60	settlement units	–0.90	–1.65	–1.48	–2.13	0.00
		population	–0.97	–1.66	–1.84	–3.11	0.00
	60–90	settlement units	0.44	0.24	–2.22	0.00	0.00
		population	0.07	0.40	–1.28	0.82	0.00
	90–120	settlement units	0.30	0.24	3.70	2.13	0.00
		population	0.77	0.08	3.35	2.29	0.00
the Upper Oder	0–30	settlement units	–0.07	–0.24	0.00	0.00	0.00
		population	–0.24	–0.38	0.00	0.00	0.00
	30–60	settlement units	–0.55	–0.71	–2.22	0.00	0.00
		population	–0.59	–0.48	–1.95	0.00	0.00
	60–90	settlement units	0.15	0.71	2.22	–2.13	0.00
		population	0.19	0.48	1.95	–1.69	0.00
	90–120	settlement units	0.47	0.24	0.00	2.13	0.00
		population	0.64	0.38	0.00	1.69	0.00

Source: own elaboration.

Table A.19. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a (fluvial) flood with a 1% probability of occurrence in the Pregolya basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Łyna and the Węgorapa	0–30	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.01	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.04	0.24	0.00	0.00	0.00
		population	–0.01	0.18	0.00	0.00	0.00
	60–90	settlement units	0.05	–0.24	0.00	0.00	0.00
		population	0.05	–0.18	0.00	0.00	0.00
	90–120	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.02	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.20. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a (fluvial) flood with a 1% probability of occurrence on the main rivers in Poland in 2019 [%]

River	Travel time [minutes]	Accumulated components	Size of settlement unit [population]				
			up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Vistula	0–30	settlement units	–0.12	0.00	0.00	0.00	0.00
		population	–0.09	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.21	0.00	0.00	–2.13	0.00
		population	–0.24	0.03	0.00	–1.85	0.00
	60–90	settlement units	–0.18	0.00	0.00	2.13	0.00
		population	0.02	–0.03	0.00	1.85	0.00
	90–120	settlement units	0.50	0.00	0.00	0.00	0.00
		population	0.31	0.00	0.00	0.00	0.00
the Oder	0–30	settlement units	–0.04	–0.24	0.00	0.00	0.00
		population	–0.13	–0.38	0.00	0.00	0.00
	30–60	settlement units	–0.49	0.00	–0.74	0.00	0.00
		population	–0.42	0.15	–0.86	0.00	0.00
	60–90	settlement units	0.50	0.24	0.74	0.00	0.00
		population	0.52	0.23	0.86	0.00	0.00
	90–120	settlement units	0.04	0.00	0.00	0.00	0.00
		population	0.04	0.00	0.00	0.00	0.00
the Warta	0–30	settlement units	–0.06	–0.71	0.00	0.00	0.00
		population	–0.10	–0.59	0.00	0.00	0.00
	30–60	settlement units	–0.42	0.94	–1.48	–2.13	0.00
		population	–0.43	0.76	–1.61	–1.62	0.00
	60–90	settlement units	0.20	–0.24	1.48	2.13	0.00
		population	0.31	–0.18	1.61	1.62	0.00
	90–120	settlement units	0.29	0.00	0.00	0.00	0.00
		population	0.22	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.21. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a (coastal) flood with a 1% probability of occurrence in the Vistula basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Vistula	0–30	settlement units	–0.01	0.00	0.00	0.00	–2.63
		population	–0.01	0.00	0.00	0.00	–4.26
	30–60	settlement units	–0.33	0.00	–0.74	0.00	–2.63
		population	–0.29	–0.05	–0.91	0.00	–1.17
	60–90	settlement units	0.17	–0.24	0.74	0.00	2.63
		population	0.16	–0.18	0.91	0.00	1.17
	90–120	settlement units	0.03	0.00	0.00	0.00	0.00
		population	–0.03	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.22. Relative changes in the number of affected settlement units and the population residing there for 30–minute intervals of travel time to provincial capitals due to a (coastal) flood with a 1% probability of occurrence in the Oder basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population] up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Oder and the coastal strip of West Pomerania	0–30	settlement units	–0.20	–0.24	–2.22	0.00	–2.63
		population	–0.27	–0.15	–1.78	0.00	–3.70
	30–60	settlement units	–0.71	–0.24	0.74	–2.13	0.00
		population	–0.56	–0.38	0.50	–2.11	0.00
	60–90	settlement units	–0.43	–1.18	1.48	2.13	2.63
		population	0.04	–1.29	1.28	2.11	3.70
	90–120	settlement units	0.08	0.47	–1.48	0.00	–2.63
		population	0.04	0.77	–1.64	0.00	–1.02

Source: own elaboration.

Table A.23. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a complete breach of the protective structures of the service strip in the Vistula basin in Poland in 2019 [%]

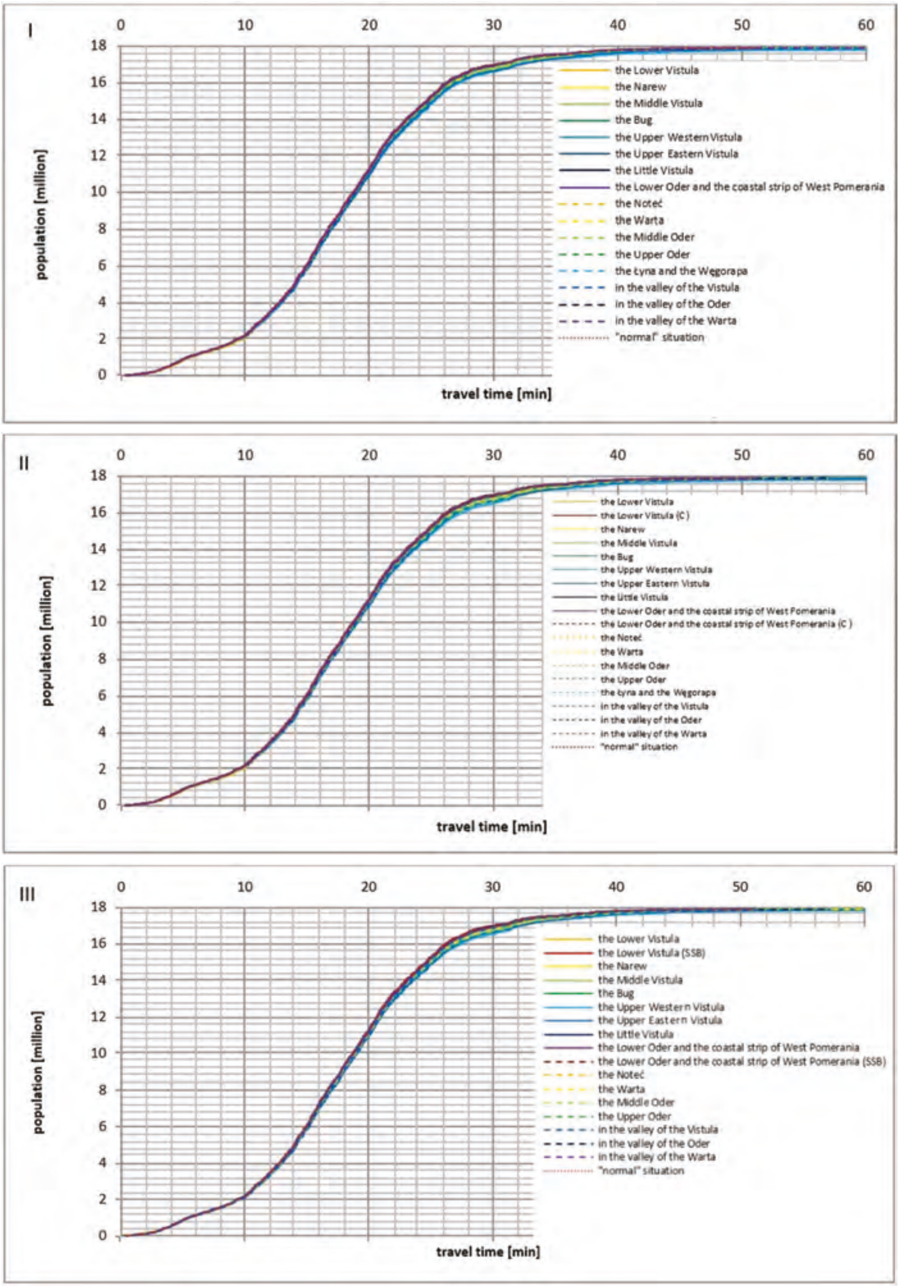
Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]: up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Vistula	0–30	settlement units	–0.08	0.00	0.00	0.00	0.00
		population	–0.09	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.41	0.00	–0.74	–2.13	–2.63
		population	–0.29	–0.05	–0.91	–1.85	–1.17
	60–90	settlement units	0.04	–0.24	0.00	0.00	2.63
		population	0.00	–0.18	0.00	0.00	1.17
	90–120	settlement units	0.05	0.00	0.00	0.00	0.00
		population	0.03	0.00	0.00	0.00	0.00

Source: own elaboration.

Table A.24. Relative changes in the number of affected settlement units and the population residing there for 30-minute intervals of travel time to provincial capitals due to a complete breach of the protective structures of the service strip in the Oder basin in Poland in 2019 [%]

Water region	Travel time [minutes]	Accumulated components	Size of settlement unit [population]: up to 5,000	5,001 to 20,000	20,001 to 50,000	50,001 to 100,000	over 100,000
			relative changes [%]				
the Lower Oder and the coastal strip of West Pomerania	0–30	settlement units	0.00	0.00	0.00	0.00	0.00
		population	0.00	0.00	0.00	0.00	0.00
	30–60	settlement units	–0.01	0.00	0.00	0.00	0.00
		population	–0.03	0.00	0.00	0.00	0.00
	60–90	settlement units	–0.07	–0.24	0.00	0.00	0.00
		population	–0.01	–0.12	0.00	0.00	0.00
	90–120	settlement units	0.07	0.24	0.00	0.00	0.00
		population	0.05	0.12	0.00	0.00	0.00

Source: own elaboration.



I – 10% probability, II – a fluvial or a coastal flood (C) with a 1% probability, III – a complete breach of stopbanks (SB) and a complete breach of the protective structure of the service strip (SSB)

Figure A.1. Temporal cumulative accessibility by population and travel time to provincial capitals under different simulated flood scenarios in Poland in 2019
Source: own elaboration

SYNOPSIS IN POLISH

Analiza literatury i opracowań badawczych poświęconych zagadnieniom wpływu zdarzeń nietypowych na funkcjonowanie transportu drogowego wskazuje, że w Polsce jest to obszar tematyczny, który jak dotąd nie uzyskał kompleksowego zainteresowania badaczy, w tym tych rozpatrujących te zjawiska z perspektywy subdyscypliny geografii transportu. O ile dostępne są niezbyt jednak liczne badania prezentujące rozważania nad wpływem czynników antropogenicznych (w tym przede wszystkim tych związanych z samą siecią transportową) na stan równowagi systemu transportowego (rozpatrywanych głównie z punktu widzenia inżynierii ruchu), to niemalże nie występują analizy poświęcone oddziaływaniu czynników przyrodniczych na funkcjonowanie transportu. Tutaj właśnie uwidacznia się luka, której zapełnienie powinno skupić się w pierwszej kolejności na usystematyzowaniu relacji na styku transportu drogowego i zjawisk nietypowych, determinujących jego efektywność (ze szczególnym uwzględnieniem zjawisk naturalnych), opracowaniu metodyki badania siły i zakresu przestrzennego tego oddziaływania oraz syntetycznemu wnioskowaniu na temat ich roli w polskich realiach. Przegląd krajowego dorobku naukowego z zakresu tematyki podejmowanej w monografii wyraźnie uwidacznia również brak badań realizowanych kompleksowo w rozumieniu przestrzennym. Chodzi zarówno o prowadzenie analiz w różnych skalach przestrzennych (lokalnych, regionalnych i ponadregionalnych) jak i zakresie umożliwiającym uniknięcie lub możliwie daleko idące ograniczenie efektu granicy. Gwarantuje to uchwycenie prawidłowości typowych dla systemów transportowych o różnych skalach oraz zaobserwowanie zjawisk, które ujawniają się dopiero przy badaniu na tyle obszernym przestrzennie, aby umożliwić współwystępowanie zjawisk (np. wystąpienie ich w różnych obszarach systemu transportowego jednocześnie). Przedstawiana czytelnikowi monografia wydaje się wypełniać również tę lukę badawczą. Potrzebę realizacji badań poświęconych zmianom dostępności transportowej i obciążenia sieci drogowej na skutek wystąpienia powodzi w Polsce uzasadnia też aktualność tej tematyki na arenie międzynarodowej, gdzie wciąż dynamicznie przyrasta liczba publikacji, specjalistycznych konferencji naukowych czy też dedykowanych tej tematyce czasopism. Uzasadnione wydaję się więc aby i w krajowym dorobku naukowym pojawiały się publikacje w tym wątku, opierające się na materiałach źródłowych obrazujących polskie uwarunkowania tychże zjawisk.

Istotności prowadzenia badań dotyczących wpływu klęsk naturalnych na transport drogowy należy upatrywać w systematycznie wzrastającym wpływie na życie ludzi obu tych elementów. Nawet nie zagłębiając się w rozważania naukowe a pozostając jedynie przy doniesieniach medialnych czy własnych obserwacjach, dostrzec można intensyfikację ekstremalnych zjawisk pogodowych, które przy zaistnieniu odpowiednich okoliczności, mogą przerodzić się w sytuację kryzysową, zagrażającą funkcjonowaniu transportu drogowego. Dotychczasowy stan wiedzy wskazuje, że powodzie są najczęstszymi katastrofami naturalnymi występującymi na świecie, które generują do tego ogromne szkody. Niestety badacze są zdania, że ekstremalne zjawiska powodziowe będą występować coraz częściej ze względu na zmiany klimatu i użytkowania terenu. Z drugiej zaś strony, XXI wiek to w Polsce niezwykle dynamiczny wzrost poziomu motoryzacji i ilości oraz jakości infrastruktury drogowej. Oczywista niewspółmierność obu tych przyrostów nie pozostaje rzecz jasna bez wpływu na obciążenie sieci drogowej. To zaś wymusza na zarządcach sieci ale i na jej projektantach coraz to większą presję na sprostanie przyrastającemu popytowi. Występują ponadto sytuacje, kiedy ta presja staje się szczególnie silna, gdy w wyniku wystąpienia zdarzeń nietypowych (np. powodzi) zarządzanie systemem transportowym jest szczególnie trudne. Wymagane jest wtedy szczególnie racjonalne i efektywne dysponowanie infrastrukturą, tak aby wobec wyłączeń wybranych jej odcinków, spadków poziomu dostępności i zmian w obciążeniu sieci, nie dopuścić do wykluczenia transportowego rzutującego na bezpieczeństwo ludności i stan gospodarki. Wystąpienie zjawisk nietypowych w postaci np. zniszczenia odcinka drogi przez wody powodziowe, skutkować może również swoistym zestawem zachowań użytkowników sieci transportowej, które zdają się stanowić problematykę na tyle ciekawą i odmienną od przebadanych już zachowań transportowych, że również należy się jej gruntowna analiza. Ujawnia to żywotną potrzebę prowadzenia tego rodzaju badań, tak aby w przyszłości mogły się one przyczynić do bardziej efektywnego reagowania w przypadku wystąpienia sytuacji kryzysowych.

Tym samym istotności badań o problematyce zmian dostępności transportowej i obciążenia sieci drogowej w sytuacji wystąpienia powodzi upatrywać należy w dwóch sferach. Niezależnie od funkcji utylitarnych związanych z zarządzaniem infrastrukturą krytyczną (do której należy infrastruktura transportowa) w sytuacji wystąpienia sytuacji kryzysowej oraz ograniczaniem potencjalnych negatywnych skutków szczególnie w zakresie życia i zdrowia ludzi oraz działalności gospodarczej (nadrzędny cel zarządzania ryzykiem powodziowym), tematyka ta ujawnia również ważny wymiar poznawczy. Przyczynia się do zidentyfikowania wrażliwości polskiej sieci drogowej oraz funkcjonującego w oparciu o nią transportu drogowego na niszczące działanie wód powodziowych, mogących wystąpić w poszczególnych regionach kraju, w scenariuszu o określonym prawdopodobieństwie. Daje możliwość wskazania obszarów szczególnie narażonych na negatywne konsekwencje powodzi w sferze efektywności systemu transportowego. W związku z tym tak ważna jest ocena potencjalnych szkód, które mogą wystąpić na skutek powodzi. W literaturze najczęściej podejmowana jest tematyka szacowania bezpośrednich strat materialnych. Straty pośrednie, ze względu na to, że są trudne do wyrażenia, zazwyczaj są pomijane. Prowadzenie badań na styku tematyki powodziowej, dostępności transportowej i mobilności ma szczególnie znaczenie ze względu na wykluczenie transportowe spowodowane zjawiskiem powodzi. Przynieść to może nie tylko paraliż transportowy, ale również administracyjny, nawet w skali całego kraju, który zagrażać może stabilności bezpieczeństwa państwa.

W monografii podjęto się próby określenia wpływu wystąpienia zdarzenia nietypowego w postaci powodzi (w różnych scenariuszach prawdopodobieństwa) na obszarach poszczególnych regionów wodnych w Polsce na dostępność transportową i obciążenie sieci drogowej kraju. Badania prowadzono głównie w oparciu o wtórne dane dotyczące zasięgów obszarów zagrożonych powodzią w Polsce i ich zagospodarowania oraz sieci drogowej wraz z zagospodarowaniem jej sąsiedztwa.

Celem opracowania jest więc określenie wrażliwości osobowego transportu drogowego w Polsce, poprzez identyfikację charakteru i skali zmian dostępności transportowej oraz zmian obciążenia sieci osobowym ruchem drogowym w sytuacji powodzi o wysokim prawdopodobieństwie wystąpienia (10%), średnim prawdopodobieństwie wystąpienia (1%) od strony rzeki i morza oraz na terenach zagrożonych powodzią w wyniku całkowitego zniszczenie obwałowania i budowli ochronnej pasa technicznego w Polsce.

Z tak sformułowanego celu głównego monografii wynika grupa szczegółowych celów o charakterze poznawczym, metodycznym oraz aplikacyjnym. W zakresie zadań poznawczych wymienić należy zidentyfikowanie uwarunkowań (między innymi przyrodniczych i prawno-administracyjnych) funkcjonowania i rozwoju sieci drogowej na terenach zagrożonych powodzią. Realizacja tego celu pozwoliła między innymi na opracowanie metodyki wyznaczania odcinków sieci drogowej wyłączonej z użytkowania podczas powodzi (jeden z celów metodycznych) oraz umożliwiła sformułowanie rekomendacji dla polityki transportowej i przestrzennej dla obszarów narażonych na zalanie. Kluczowymi celami szczegółowymi w zakresie poznawczym było natomiast określenie charakteru i skali zmian dostępności czasowej – izochronowej/kumulatywnej i potencjałowej (w ujęciu gminnym) towarzyszących wystąpieniu powodzi oraz zidentyfikowanie cech zmian wielkości potoków ruchu (związanych z motywacjami obligatoryjnymi) wynikających z wyłączeń zalanych odcinków sieci i redukcji wielkości potencjałów ruchotwórczych.

Pierwszym z celów o charakterze metodycznym było opracowanie postępowania służącego identyfikowaniu odcinków sieci drogowej zagrożonych zalaniem w wyniku wystąpienia powodzi o wysokim i średnim prawdopodobieństwie oraz w związku z całkowitym zniszczeniem obwałowań lub budowli ochronnej pasa technicznego. Drugi natomiast, dotyczył budowy modelu sieci drogowej i prędkości osobowego ruchu drogowego w Polsce, o gęstości sieci umożliwiającej analizy wewnątrzgminne. Jest to narzędzie niezbędne do prowadzenia analiz dostępności transportowej, umożliwiające urealnianie uzyskiwanych wyników. Duża szczegółowość modelu jest niezbędna aby mógł on w akceptowalny sposób odzwierciedlać nawet lokalne zmiany w systemie transportowym wywołane powodzią. Ostatnie zadanie z tej grupy celów koncentrowało się na przygotowaniu oprogramowania komputerowego (noszącego nazwę RoadLoad), umożliwiającego realizację procesu rozmieszczenia popytu na sieć systemu transportowego, którego wyniki działania pozwalają na skuteczne badanie i wizualizowanie zmian rozkładu ruchu na sieć towarzyszących wystąpieniu zjawisk nietypowych. Jest to jednocześnie cel aplikacyjny, ponieważ oprogramowanie wraz z licznymi jego funkcjonalnościami dedykowanymi modelowaniu rozkładu ruchu na sieć drogową, posłużyć może do kolejnych analiz tego rodzaju, chociażby uwzględniających kolejne grupy zdarzeń nietypowych. Zbiór celów szczegółowych zamyka ostatnie zadanie o charakterze aplikacyjnym jakim jest sformułowanie rekomendacji na potrzeby polityki przestrzennej w zakresie racjonalizacji systemu osobowego transportu drogowego w sytuacji zagrożeń powodziowych. Płynące z badania wnioski zostaną przełożone na zespół rekomendacji skierowanych do decydentów odpowiedzialnych za kreowanie polityki w zakresie zarządzania ryzykiem powodziowym czy rozwojem infrastruktury transportowej.

Monografia zawiera wyniki projektu badawczego zatytułowanego *Zmiany teoretycznej dostępności transportowej i obciążenia sieci drogowej na skutek wystąpienia powodzi na terytorium Polski* realizowanego przez Instytut Zagospodarowania Środowiska i Polityki Przestrzennej Uniwersytetu Łódzkiego w latach 2019–2021. Projekt o numerze 2018/29/B/HS4/01020 został sfinansowany z środków przyznanych przez Narodowe Centrum Nauki.

Prezentowane w monografii analizy odnoszą się do trzech obszarów tematycznych: zagospodarowania terenów zagrożonych powodziami, dostępności transportowej oraz mobilności przestrzennej (ujmowanej tutaj w formie jednego z jej produktów, jakim jest ruch drogowy). Badanie zostało przeprowadzone przy założeniu, że potencjalne przemieszczenia odbywają się za pomocą indywidualnego transportu samochodowego. Wzajemne relacje pomiędzy wskazanymi powyżej obszarami tematycznymi przekładają się w pierwszej kolejności na badania wpływu powodzi na dostępność transportową w ujęciu czasowym. Chodzi tutaj o identyfikację tych odcinków sieci drogowej, które podczas powodzi znajdą się pod wodą. Na bazie sieci drogowej pozbawionej zalanych odcinków konstruowane są między innymi izochrony dojazdu do przyjętych punktów referencyjnych (np. centroidów miast wojewódzkich). Zestawienie przebiegu izolinii w okresie bez powodzi i podczas jej wystąpienia pozwala na wymierną ocenę poziomu wydłużenia czasów przejazdu na skutek zalania. Wyznacznikiem zmian dostępności jest również liczba ludności i elementy zagospodarowania przestrzeni Polski, znajdujące się w zasięgu poszczególnych izochron w sytuacji „normalnej" i podczas powodzi. Drugi z poruszanych problemów skupia się między innymi na identyfikacji przepływów pojazdów na sieci drogowej w sytuacji bez powodzi i podczas klęski żywiołowej, przyjmując kilka wariantów badawczych. Dla zobrazowania przejazdów konieczne jest przyjęcie danych o źródłach i celach podróży oraz wolumenie pojazdów, które się pomiędzy nimi przemieszczają. W opracowaniu przeanalizowano i zobrazowano przejazdy związane z motywacjami obligatoryjnymi – względnie stałymi nawet wobec wystąpienia zdarzeń nietypowych (dojazdy do pracy i podróże biznesowe). Przeanalizowano wielkości przepływów pojazdów – obciążenie sieci drogowej w sytuacji „normalnej" i podczas powodzi pod kątem między innymi zmian w obciążeniu poszczególnych odcinków sieci, czy struktury zróżnicowania obciążenia sieci według kategorii drogi.

Zakres badań podejmowanych w monografii wpisuje się przede wszystkim w dwa główne cele zarządzania ryzykiem powodziowym – obniżenie istniejącego ryzyka i poprawę systemu zarządzania nim, a w ich zakresie szczególnie w: ograniczenie wrażliwości obiektów (w tym przypadku infrastruktury transportowej) i społeczności (które można wprost postrzegać jako użytkowników infrastruktury transportowej) na zagrożenia powodziowe, doskonalenie skuteczności odbudowy (sieci drogowej) i powrotu (sytemu transportowego) do stanu sprzed powodzi oraz w budowę programów edukacyjnych poprawiających świadomość i wiedzę na temat źródeł zagrożenia i ryzyka powodziowego (np. podczas samoewakuacji ludności z terenów zagrożonych).

Zakres czasowy badania został w znacznej mierze zdeterminowany przez dostępność kluczowych źródłowych baz danych wykorzystywanych w monografii. Duże rozpiętości czasowe ujawniające się podczas przygotowywania danych wynikają z jednej strony ze złożoności metodyki pracy nad nimi, z drugiej zaś z rozległości obszaru, z którego musiały zostać zebrane a następnie opracowane. Rodzi to problem zróżnicowania przestrzennego aktualności tychże danych źródłowych, którego rozwiązanie stanowiło istotne wyzwanie metodyczne. Model sieci i prędkości przedstawiają stan na III kwartał 2019 r. i okres ten należy przyjąć jako generalny zakres czasowy opracowania. Uwzględniono go również dokonując przeglądu i interpretacji prawodawstwa z zakresu podejmowanej tematyki. Część materiału statystycznego w zakresie danych w układzie produkcja-atrakcja dla motywacji dotyczącej dojazdów do szkoły oraz podróży biznesowych odnosi się do roku 2018. W przypadku danych macierzowych uzyskanych dla dojazdów do pracy, ich dostępność również wymagała pewnego przesunięcia czasowego, ponieważ najnowsze zestawienie tego typu obejmuje rok 2016.

Zakres przestrzenny badania jest ściśle związany z siecią drogową, której model objął cały obszar Polski oraz kilkudziesięciokilometrowy bufor wokół jej granic. Sieć obejmuje wszystkie autostrady, drogi ekspresowe, krajowe, wojewódzkie, powiatowe oraz znaczny udział dróg gminnych i lokalnych. Zastosowany bufor miał za zadanie urealnić wyniki symulacji, umożliwiając pojazdom omijającym wyłączone z sieci odcinki dróg (na skutek zniszczenia przez powódź), ewentualne wykorzystywanie infrastruktury położonej poza granicami Polski. Badania prowadzono przy uwzględnieniu trzech scenariuszy wystąpienia powodzi: na terenach zagrożonych powodzią o wysokim prawdopodobieństwie wystąpienia (10%), na terenach zagrożonych powodzią o średnim prawdopodobieństwie wystąpienia (1%) (w tym od strony morza 1%M) oraz na terenach zagrożonych powodzią w wyniku całkowitego zniszczenie obwałowania (WZ) i budowli ochronnej pasa technicznego (PZ). Symulacje wystąpienia powodzi wykonywano dla każdego z trzynastu regionów wodnych w Polsce w dorzeczu Wisły, Odry i Pregoły oraz dla trzech największych rzek Wisły, Odry i Warty. Każda próba ujęcia tak złożonego zjawiska jakim jest powódź w jakiekolwiek granice zawsze będzie dyskusyjne. Ze względu jednak na konieczność uwzględnienia jego zmienności przestrzennej, niezbędne było przyjęcie jakiejś delimitacji. Sięgnięto po regiony wodne (rezygnując np. z jednostek podziału administracyjnego), ponieważ jako jednostki wyodrębnione na podstawie kryterium hydrograficznego wydają się odpowiadać realizowanemu celowi opracowania a ich liczba i rozkład przestrzenny umożliwiają przeprowadzenie symulacji pozwalających uchwycić zróżnicowanie cech relacji systemu transportu drogowego i tego rodzaju sytuacji nietypowej w polskich realiach. Na bazie tak przyjętego planu symulacji powodzi, badania zmian dostępności transportowej prowadzono na poziomie regionalnym i gminnym, natomiast analizy zmian obciążenia sieci drogowej przyjęły międzygminną skalę precyzji.

Dokonany przegląd zdarzeń nietypowych, jakie mogą wpływać na funkcjonowanie transportu drogowego w Polsce, wskazuje, że znaczna ich część dotyczy relacji woda-infrastruktura drogowa i woda-pojazd. Całkowita liczba możliwych konsekwencji wzajemnego oddziaływania na siebie tych par czynników jest trudna do określenia, niemniej jednak część z nich została już gruntownie przebadania na polu różnych dyscyplin naukowych. Formą oddziaływania wody na infrastrukturę drogową i jej użytkowników, która wystawia te elementy systemu transportowego na szczególną próbę, jest wystąpienie powodzi. Różnorodność form jej oddziaływania, które przy odpowiedniej kombinacji wielkości zagrożenia, ekspozycji i wrażliwości, mogą stanowić istotną barierę transportową, potwierdzają liczne, tragiczne w skutkach, doświadczenia historyczne.

Świadczą one również, wraz z wynikami wielu prac badawczych, że pojawienie się symptomów zagrożenia czy też jego rzeczywiste wystąpienie może przyczynić się do realizacji przemieszczeń ludności związanych z ucieczką przed niebezpieczeństwem. Przeanalizowane wyniki badań oraz zapisy różnorodnych wytycznych dotyczących realizacji procesu ewakuacji w sferze organizacji transportu, wskazują że problematyka jego optymalizacji stanowi wyzwanie zarówno jako przedmiot rozważań teoretycznych jak i praktycznych. Oba te podejścia uwzględniają zazwyczaj wzajemną zależność pomiędzy przemieszczeniami realizowanymi w związku z ewakuacją a mobilnością wynikającą z realizacji innych, „zwykłych" motywacji podróży. Wyniki ich obopólnego odziaływania mogą przyjąć tak różne skutki w obrębie obu grup przemieszczeń, jak zróżnicowane mogą być okoliczności ich realizacji. Niejednolitość wdrażanych narzędzi optymalizacji procesu ewakuacji, zróżnicowanie poziomów równowagi systemu transportowego, a przede wszystkim różnorakość cech użytkowników systemu i ich reakcji na zagrożenie oraz zmienność cech samego zagrożenia, wskazuje że uwzględnienie ewakuacji jako czynnika wpływającego na funkcjonowanie transportu drogowego jest uzasadnione. Jednocześnie aby dawało realne wyniki, konieczne jest wzięcie pod uwagę lokalnych uwarunkowań i również takiej skali przestrzennej analiz.

Analiza wybranych cech powodzi w Polsce wskazuje, że generują one najwyższe szkody w Polsce południowej (w dorzeczu górnej i środkowej Odry oraz górnej Wisły), co w znacznej mierze znalazło swoje potwierdzenie również w przypadku konsekwencji w zakresie ingerencji w sieć drogową i perturbacji dla całego krajowego systemu transportu drogowego. Badanie wybranych cech środowiska przyrodniczego oraz elementów zagospodarowania terenów zagrożonych powodzią, poszerzona o badanie rozmieszczenia ludności, pozwoliła na określenie zasadniczych uwarunkowań funkcjonowania i rozwoju sieci drogowej na tych terenach. Uwzględnienie realiów prawno-administracyjnych towarzyszących gospodarowaniu na terenach zagrożonych wskazuje, że kluczowym elementem chrakteryzującym zarządzanie terenami zagrożonymi klęską żywiołową powinna być stabilność kluczowych zasad mu przyświecających – opornych na koniunkturę gospodarczą. Zmienność zasad gospodarowania na tych terenach, choć zapewne występująca w dobrej wierze, uniemożliwia wykrystalizowanie się zakładanych pozytywnych rezultatów ze względu na zbyt wąski horyzont czasowy, który wyznacza kolejna zmiana. Każdej z nich musi towarzyszyć okres przejściowy, który wprowadza element niepewności i jest potencjalną areną dla wystąpienia nadużyć i nieprawidłowości. Dla sieci drogowych problematyczna jest również niespójność ustaleń i to zarówno w rozumieniu przestrzennym jak i rzeczowym. Nawet najrzetelniej prowadzona polityka przestrzenna chroniąca tereny zalewowe przed niepożądanym zagospodarowaniem przez jedną z nadrzecznych gmin nie przyniesie pozytywnych efektów zewnętrznych jeśli jej sąsiedzi traktować ją będą jako barierę na drodze rozwoju lokalnego. Poprzez budowanie świadomości społecznej i odpowiedzialności środowiskowej należy dążyć do sytuacji, w której bez działań zagrażających samorządności poszczególnych społeczności lokalnych w kwestii gospodarowania ich przestrzenią, będzie można liczyć na ich czynny udział w prawidłowym kształtowaniu roli tych terenów, któremu towarzyszyć będzie spadek ich ruchotwórczości.

Przegląd materiałów źródłowych odnoszących się do zasady budowy i eksploatacji infrastruktury drogowej na terenach zagrożonych, daje szeroki zakres przepisów i dobrych praktyk, których wdrażanie gwarantować ma możliwie wysoki poziom odporności infrastruktury na niszczące oddziaływanie wód powodziowych. Ich duża liczba i bogaty zakres tematyczny poruszanych wątków potwierdza, że istotność tego czynnika dla funkcjonowania transportu drogowego została już gruntownie usankcjonowana na polu projektowania i realizacji inwestycji. Bogaty zasób dokumentacji warunkującej zarządzanie systemem transportu drogowego wobec wystąpienia sytuacji kryzysowej dowodzi jednak, że nawet najrzetelniejsze wypełnianie wytycznych może nie zagwarantować odporności wystawionych na oddziaływanie powodzi segmentów sieci drogowej. Dostrzegając w tego rodzaju zdarzeniach nietypowych niebezpieczeństwo dla stabilności funkcjonowania struktur państwowych, opracowane zostały dokumenty o charakterze strategicznym i operacyjnym, w myśl których uzyskane w niniejszej monografii rezultaty dają niezbędny materiał diagnostyczny dla poprawy bezpieczeństwa systemu transportu drogowego. Wypracowana metodyka oceny wpływu powodzi na funkcjonowanie transportu drogowego pozwala bowiem na ujęcie zagrożeń nawet o bardzo małym prawdopodobieństwie i katastrofalnych skutkach. Dzięki identyfikacji tych elementów sieci, których zniszczenie lub zakłócenie ich funkcjonowania przyniosło najdalej idące konsekwencje dla dostępności transportowej i obciążenia sieci drogowej, organy zaangażowane w zarządzanie infrastrukturą krytyczną (operatorzy) są w stanie przygotować i wdrażać plany ochrony infrastruktury krytycznej o treści wierniej dopasowanej do zamodelowanych zmian. Daje to również możliwość efektywniejszego rozporządzania własnymi zasobami rezerwowymi. Dzięki przeprowadzonym symulacjom możliwym jest sprawniejsze rozlokowywania w przestrzeni i czasie sił i środków zapewniających bezpieczeństwo i podtrzymujących funkcjonowanie infrastruktury drogowej do czasu jej pełnego odtworzenia. Uzyskane w niniejszym badaniu rezultaty mogą tym samym ułatwić spełnienie standardów zarządzanie infrastrukturą krytyczną. Dane o rozmieszczeniu obszarów szczególnie narażonych na ograniczenie dostępności, pozwalają na podjęcie z odpowiednim wyprzedzeniem działań gwarantujących utrzymanie wysokiej dostępności infrastruktury transportu drogowego w dowolnym czasie. Wskazanie odcinków sieci, które są potencjalnie zagrożone zalaniem lub „odcięciem" oraz tych, które przyjmą na siebie ich rolę w rozprowadzaniu ruchu drogowego, umożliwia spełnienie postulatu niezawodności w kontekście wzajemnej zastępowalności poszczególnych jej elementów. Sprecyzowanie krytycznych elementów sieci (jednocześnie zagrożonych i istotnych) znacznie ułatwia również utrzymanie niezawodności w sferze realizacji napraw doraźnych i planowych i ich harmonogramowania.

Żadne z powyższych możliwości wspomagania zarządzania infrastrukturą czy wręcz systemem transportu drogowego nie byłoby możliwe bez zidentyfikowania miejsc, w których stosunek zagrożenia do ekspozycji i wrażliwości infrastruktury jest na tyle niekorzystny, że musi ona zostać wyłączona z eksploatacji. Opracowanie postępowania służącego identyfikowaniu odcinków sieci drogowej zagrożonych zalaniem w wyniku wystąpienia powodzi o wysokim i średnim prawdopodobieństwie oraz w związku z całkowitym zniszczeniem obwałowań lub budowli ochronnej pasa technicznego już na etapie koncepcji wydawało się dużym wyzwaniem. Wiązało się bowiem z pracą na bardzo dużych zbiorach danych o zróżnicowanej przestrzennie aktualności. Towarzysząca przejściu z etapu koncepcyjnego do operacyjnego kontrola kompletności i poprawności danych ujawniła potrzebę wprowadzenia dodatkowego procesu szczegółowej weryfikacji sytuacji w przypadku drogowych obiektów inżynierskich i nowych inwestycji. Wiązało się to z pozyskaniem bardzo obszernego materiału źródłowego od instytucji zaangażowanych w realizację drogowych inwestycji infrastrukturalnych. Materiał ten również cechuje się wyraźnym zróżnicowaniem w zależności od terytorium jakie obejmuje. Tutaj jednak zmienność dotyczy głównie formy i objętości treściowej zapisów. Niemniej jednak, kosztem znacznego wzrostu czaso- i pracochłonności, możliwym stało się określenie rozmieszczenia zagrożonych odcinków sieci drogowej w Polsce. Trudności towarzyszące analizie i interpretacji zapisów w zbiorczej dokumentacji dotyczącej realizacji inwestycji w infrastrukturze drogowej, uzasadniają postulat większej unifikacji treści opisującej inwestycję a sporządzanej przez różne organy, o różnym zasięgu terenowym. Wobec niedogodności związanych z dostępem do dokumentacji projektowych i jej analizą, takie ujednolicenie i uszczegółówcie zapisów na poziomie wykazu, byłoby znacznym ułatwieniem.

Pozostając w tematyce baz danych, wykazów i dokumentacji, zasygnalizować należy braki i nieaktualności występujące w charakterystyce nawet podstawowych parametrów technicznych obiektów inżynierskich (mostów, przepustów) ujmowanych np. w ogólnodostępnych wektorowych bazach danych. Mając na względzie strategiczną rolę tego typu obiektów dla obronności państwa, można jednak postulować dopracowanie istniejących lub utworzenie nowych baz danych, których zakres opisanych parametrów mógłby być powszechnie dostępny i nie zagrażałby bezpieczeństwu kraju. Poza ogromnym ułatwieniem w dostępnie do informacji, wiązałoby się to również ze standaryzacją zapisów, które aktualnie zawarte są najczęściej w licznych dokumentach o różnej aktualności i dostępności. Wykorzystanie w szerszym zakresie informacji o cechach konstrukcji budowli inżynierskich dałoby możliwość większego zróżnicowania ich „reakcji" na zagrożenie na etapie budowy modeli sieci drogowych dla poszczególnych scenariuszy powodziowych.

Z punktu widzenia badań dotyczących transportu drogowego niezwykle cenne byłoby również uszczegółowienie informacji o poziomie wody powodziowej w obrębie obecnie funkcjonującego pierwszego przedziału – do 50 cm. Przegląd badań wskazuje, że nawet kilkunastocentymetrowe różnice poziomu wody mogą przynieść bardzo różne skutki dla funkcjonowania sieci i realizowanych na niej podróży. Wartości progowe są nadal dyskusyjne i nie ma co do nich zgodności w stosowanej w badaniach metodyce, co nie zmienia faktu, że cenna była sama możliwość włączenia się w tego typu dywagacje. Mając na uwadze wielkość zasobów (danych, mocy obliczeniowej itd.) niezbędnych dla zamodelowania wartości poziomu wody powodziowej, wprowadzenie chociażby jednego dodatkowego przedziału klasowego (np. do 25 cm) byłoby modyfikacją mogącą zaowocować dużym potencjałem dodatkowych pól badawczych.

Dalsze badania mogłyby odnosić się również do prężności systemu transportowego, dzięki uwzględnieniu zmienności zjawiska powodzi w czasie. Chodzi tutaj zarówno o przemieszczanie się fali powodziowej ale też okres po jakim woda ustąpi i możliwe będzie rozpoczęcie działań zmierzających do przywrócenia sieci drogowej do stanu pierwotnego. Otworzyłoby to drogę dla analiz związanych z czasowym przesunięciem podróży. Niestety dane odnoszące się do dynamiki czasowo-przestrzennej zjawiska, dla przyjętej skali badania nie są dostępne, dlatego też ich uwzględnienie nie było możliwe. Cennym uzupełnieniem zaprezentowanego podejścia modelowego byłoby włączenie informacji na temat zmian zachowań komunikacyjnych ludności w czasie tak szczególnym jak okres zagrożenia, wystąpienia powodzi oraz etap powrotu do sytuacji wyjściowej. Jest to jednak zadanie wyjątkowo trudne, bowiem możliwość przeprowadzenia analiz w czasie trwania rzeczywistego zagrożenia jest uwarunkowana prawdopodobieństwem wystąpienia klęski a dodatkowo ograniczana dużą dynamiką zjawiska i oczywiście okolicznościami zniechęcającymi do udziału we wszelkiego rodzaju badaniach społecznych. Jednakże zaspokajałoby to poniekąd potrzebę większego zaangażowania czynnika ludzkiego w tego rodzaju badaniach, dając np. możliwość bardziej precyzyjnego określenia elastyczności popytu drogowego, oporu przestrzeni czy przesunięcia modalnego, które charakteryzowałby sytuacje kryzysową.

Dalsze badania mogłyby zostać ukierunkowane również na wprowadzenie innych motywacji podróży, czy wręcz zastosowanie wielomotywacyjnego modelu ruchu. Ruch związany z dojazdami do pracy i podróżami służbowymi stanowi jedynie część (choć znaczącą) potoków ruchu towarzyszących wszelkim motywacjom i w związku z tym nie możliwe jest w oparciu jedynie o te motywację pełne wnioskowanie o poziomie zatłoczenia sieci czy wynikających z tego spadkach prędkości (z tej przyczyny zastosowano model urzeczywistniający prędkość przejazdu). Dlatego też możliwym jest przeprowadzenie zastosowanego w monografii postępowania badawczego również dla zmiennych charakterystycznych dla kolejnych motywacji i długości podróży a następnie rozłożenie ruchu uwzględniającego strukturę poszczególnych celów podróży w potokach pojazdów na sieci drogowej. Niepewne wydaje podejmowanie wątku podróży międzynarodowych czy też drogowego transportu towarowego, bowiem jak wykazały badania, infrastruktura drogowa odpowiedzialna w zasadniczej mierze za obsługę tego ruchu pozostaje w większości przypadków poza spektrum bezpośredniego oddziaływania wód powodziowych. Otwarta pozostaje jednak kwestia wpływu pośredniego, w postaci np. wzmożonego ruchu pojazdów objeżdżających zalane tereny w związku z realizacją m.in. dojazdów do pracy.

Samo zdefiniowanie zmian w sieci drogowej, powstających w związku z powodzią, to jedynie podstawa dla określenia jak modyfikacje te mogą przełożyć się na jej użytkowanie. Temu zadaniu służyło opracowanie modelu prędkości ruchu drogowego oraz implantacja metod oceny zmian dostępności transportowej i obciążenia sieci drogowej. Zaproponowane podejście do wyznaczania prędkości poruszania się pojazdów po poszczególnych, dalece zróżnicowanych pod kątem stopnia swobody ruchu odcinkach sieci o dużej szczegółowości, wydaje się dobrze spełniać swoją rolę. Założenia modelu i jego późniejsza kalibracja pozwoliła na uzyskanie narzędzia badawczego obejmującego zarówno szeroki zakres przestrzenny badania jak i wysoką rozdzielczość modelu sieci drogowej przy jednocześnie akceptowalnym poziomie rozbieżności uzyskiwanych wyników względem przyjętego wzorca. Nie zmienia to jednak faktu, że mimo starań aby model najelastyczniej dopasowywał prędkość do okoliczności podróży, podejście to może być traktowane nadal jako zbyt „sztywne", szczególnie wobec tak nietypowych, symulowanych okoliczności. Rozwiązania tego problemu można dopatrywać się w zastosowaniu modeli ruchu i danych o prędkości ruchu będących ich produktem. O ile rozwiązanie tego rodzaju przy zachowaniu tak wysokiego poziomu szczegółowości modelu sieci, wydaje się być realizowalne w skali lokalnej czy nawet regionalnej, to badania na szerszą skalę wydają się niezwykle trudne do przeprowadzenia.

Powiązanie badań zmian dostępności transportowej z symulacyjnymi modelami ruchu daje również możliwość określenia zmian w ruchliwości towarzyszącej ingerencjom w integralność sieci drogowej. W niniejszym badaniu, zarówno w zakresie analiz dostępności jak i natężeń ruchu, sięgnięto jednak w tym względzie do szczegółowych danych dotyczących liczby ludności zamieszkującej na terenach zagrożonych powodzią. Podejście to wysoce uprawdopodabnia skalę przyjętych redukcji potencjałów, jednak możliwe jest udoskonalenie tego rozwiązania. Poza uwzględnieniem danych o ludności zamieszkującej obszary mogące ulec zalaniu, wskazane byłoby również zinwentaryzowanie wszelkich innych generatorów ruchu i zdefiniowanie wielkości redukcji ruchu jaka mogłaby towarzyszyć ich niefunkcjonowaniu w związku z powodzią. Tak szczegółowe analizy również wydają się być możliwe przede wszystkim na poziomie lokalnym. Podobnie zresztą jak próby kalibracji modelu odzwierciedlającego rozkład ruchu w związku z wystąpieniem zdarzenia nietypowego w postaci powodzi. Rozważyć można ponadto zastosowanie innego niż deterministyczny rozkład równowagi użytkownika podejścia do rozkładu ruchu na sieć transportową w czasie symulacji w czasie trwania powodzi, ze względu na dużą dynamikę zjawiska i trudność w pozyskiwaniu wiedzy o najkrótszej trasie wobec zmieniających się szybko okoliczności.

Wszystkie wymienione dotychczas rezultaty realizacji poznawczych i metodycznych szczegółowych celów opracowania umożliwiły finalnie realizację celu głównego – określania wrażliwości osobowego transportu drogowego w Polsce, poprzez identyfikację charakteru i skali zmian dostępności transportowej oraz zmian obciążenia sieci osobowym ruchem drogowym. Dla obu zakresów tematycznych przeprowadzono symulacje przy uwzględnieniu pięciu różnych scenariuszy powodzi oraz przy zróżnicowaniu przestrzennym uwzględniającym obszary poszczególnych regionów wodnych w Polsce i dodatkowo warianty obejmujące doliny głównych rzek kraju. Zrealizowane badania wskazały, że system transportu drogowego charakteryzuje się zróżnicowaną przestrzennie wrażliwością na wystąpienie zdarzeń nietypowych w zakresie obniżenia dostępności transportowej i cech eksploatacji sieci drogowej. Ujawnia się ona zarówno w zakresie komponentu transportowego jak i zagospodarowania/komponentu demograficznego. Uzyskane rezultaty ujawniają ponadto zróżnicowanie siły ingerencji w bazowe poziomy dostępności jak i natężeń ruchu drogowego, ze względu na przyjęte długości podróży oraz ich motywacje.

Bez względu na długość rozpatrywanych podróży, w przypadku wystąpienia zagrożenia od strony rzeki, szczególnie niekorzystna z perspektywy dostępności transportowej sytuacja może dotyczyć północnej części województwa mazowieckiego oraz znacznego udziału terytorium województw Polski Wschodniej. Obszary o niskim bazowym poziomie dostępności i jego dużej redukcji w związku z powodzią uzupełnia południowa cześć Małopolski, północna Wielopolska oraz Nizina Śląska, Przedgórze Sudeckie czy Pojezierze Lubuskie. Pomorze Zachodnie nie zostaje objęte istotnym spadkiem dostępności w związku z zagrożeniami od strony rzeki. Pozostaje jednak, wraz z miastami województw pomorskiego i warmińsko-mazurskiego, w zasięgu ponadprzeciętnego obniżenia dostępności na skutek powodzi od strony morza. Należy aczkolwiek pamiętać, że odnotowane dla tych scenariuszy powodziowych redukcje, przyjmowały bardzo niewielkie wartości procentowe. Do grupy obszarów stanowiących bieguny najwyższej bazowej wartości dostępności, które mogą zostać dotknięte istotnym obniżeniem dostępności w związku z powodzią należą szczególnie: gminy na północ i północny zachód od Warszawy, okolice Bydgoszczy (w przypadku podróży długich) oraz obszary nawiązujących przebiegiem do autostrady A4 na odcinkach Wrocław–Opole oraz Kraków–Rzeszów. W przypadku gdy podróż jest motywowana dotarciem do miejsc pracy, szczególnie wysokie przyrosty liczby pojazdów występują zazwyczaj na fragmentach sieci sąsiadujących z dużymi aglomeracjami. Badania wskazują, że sieć drogowa charakteryzuje się najczęściej na tyle wysokim poziomem opcjonalności ścieżek przejazdu, że zalanie określonego jej odcinka wiąże się zazwyczaj z koniecznością objazdu a nie rezygnacji z podróży. Ten przeważnie niewielki, lokalny przełożony przestrzennie ruchu prędzej czy później obciąży już w sposób skumulowany odcinki sieci prowadzące bezpośrednio do obszarów koncentracji miejsc pracy. Duża część prawidłowości cechujących rozmieszczenie odcinków sieci drogowej o ponadprzeciętnym wzroście obciążenia ruchem związanym z podróżami do pracy, na skutek wystąpienia powodzi, ma również miejsce w sytuacji kiedy przemieszczania wynikają z konieczności realizacji zadań (podróży) służbowych. Niemniej jednak, w sposób szczególny i nieporównywalny skalą przestrzenną do innych aglomeracji, ogniskują się one wokół Warszawy i generalnie sieci drogowej na obszarze województwa mazowieckiego.

Generalnie rzecz ujmując, powodziom o mniejszym prawdopodobieństwie czy też skutkującym zniszczeniem budowli chroniących przed zalaniem towarzyszą dotkliwsze spadki dostępności transportowej a system zmuszony jest obsłużyć większą pracę eksploatacyjną. Niejednorodność sieci drogowej i zróżnicowane względem terenów zagrożonych zalaniem, rozmieszczenie potencjału, nie pozwala aby zależność ta miała charakter wprost proporcjonalny. Związku o takiej naturze trudno doszukać się również pomiędzy zasięgiem bezpośredniego oddziaływania wód powodziowych na infrastrukturę drogową a konsekwencjami względem systemu transportu drogowego rozpatrywanych w skali ogólnopolskiej. Niemniej jednak, można wskazać grupę regionów wodnych, na terenie których powódź najdotkliwiej ingeruje w równowagę systemu transportu drogowego, w tym polaryzując będącą jego produktem dostępność. W przypadku regionów wodnych Środkowej Odry, Górnej-Zachodniej Wisły, Środkowej Wisły i Dolnej Wisły występuje bowiem jednocześnie znaczna ekspozycja i infrastruktura o dużej istotności dla całego krajowego systemu transportu drogowego oraz ośrodki o kluczowym znaczeniu dla kształtowania dostępności i rozkładu ruchu w warunkach „normalnych". Należy mieć jednak świadomość, że aktualnie realizowane pierwszoplanowe drogowe inwestycje infrastrukturalne, przyczynią się bez wątpienia do zawężania zaobserwowanych w niniejszym badaniu potencjalnych negatywnych konsekwencji dla użytkowników sieci.

Obszerność i wielowątkowość uzyskanego materiału badawczego oraz zakres potencjalnych dalszych, pogłębiających go analiz, wskazują na duży potencjał poznawczy tematyki wpływu zdarzeń nietypowych w formie powodzi na funkcjonowanie transportu drogowego. Należy mieć jednocześnie poczucie, że ze względu na złożoność podejmowanej problematyki, nie do uniknięcia jest wprowadzanie pewnych założeń upraszających czy też warunków brzegowych, których świadomość powinna towarzyszyć interpretacji otrzymanych rezultatów.

Działania zmierzające do obniżenia wrażliwości transportu drogowego na wystąpienie zdarzenia nietypowego w formie powodzi, należy prowadzić zasadniczo w odniesieniu do trzech sfer: infrastruktury drogowej i zarządzania nią, użytkowników sieci drogowej oraz pozostałego zagospodarowania terenów zagrożonych powodzią.

Działania dotyczące pierwszego obszaru tematycznego są już w znacznej części przeprowadzane, bowiem realizowane są z większą lub mniejszą systematycznością zasadnicze inwestycje infrastrukturalne służące zakończeniu krajowych planów w tym zakresie. Niemniej jednak, również z perspektywy wystąpienia perturbacji w następstwie powodzi czy też innych zdarzeń nietypowych, bardzo istotne jest ukończenie toczącego się procesu inwestycyjnego, tak aby zapewnić możliwie wysoki poziom bazowej dostępności transportowej i co ważniejsze aby poziom ten był jak najmniej zróżnicowany przestrzennie. Eliminacja obszarów wykluczonych z możliwości swobodnego i wygodnego korzystania z możliwości dostępnych w miejscach gdzie skupia się potencjał rozwojowy w okolicznościach niezaburzonej równowagi systemu transportowego, zapobiegnie nałożeniu się na siebie niskiego poziomu dostępności wyjściowej i dużej skali jego redukcji w związku z zaistnieniem zagrożenia.

Poza uniwersalnym postulatem ukończenia kluczowych inwestycji, konieczne jest jednak również podejście do polityki inwestycyjnej w sposób dostosowany do potrzeb lokalnych systemów transportu drogowego. Zróżnicowanie ich reakcji na symulowane wystąpienie zagrożenia, ujawnia wymóg przemyślanej alokacji środków inwestycyjnych nie tylko względem bieżących potrzeb infrastrukturalnych, ale przede wszystkim przy uwzględnieniu aktualnych i przyszłych cech mobilności. Dla części lokalnych sieci kluczowy będzie jedynie remont budowli inżynierskiej, zaś inne musiałby przygotować znaczny udział swoich odcinków dróg na przyjęcie ruchu pojazdów, do którego obsługi w warunkach „normalnych" nie są zdolne. Nie bez znaczenia jest również harmonogramowanie tego rodzaju działań. Konieczne jest w tym względnie nie tylko uwzględnienie doraźnych przesłanek pierwszeństwa określonej inwestycji ale również uwzględnianie prognozowanych zmian demograficznych, m.in. w kontekście zapewnienia bezpieczeństwa podczas przemieszczeń wynikających z ewakuacji. Wiąże się to pośrednio z drugą ze wskazanych sfer, w postaci wzajemnego poszanowania, dążącego do kompatybilności pomiędzy polityką transportową (bądź chociażby próbami jej formułowania) i polityką przestrzenna, szczególnie na terenach szczególnego zagrożenia powodzią ale również tam, gdzie może ono wystąpić jedynie potencjalnie. Osobnym wyzwaniem jest również powiązanie wspomnianych wcześniej kluczowych inwestycji z sieciami lokalnymi. „Punkty styku" obu tych skali powinny stanowić przedmiot szczególnie wnikliwych analiz, również ze względu na ich podatność na wystąpienie różnego rodzaju zdarzeń nietypowych, w tym powodzi.

Rezultaty badań podjętych w niniejszej monografii uzasadniają potrzebę sporządzania analiz zmian dostępności transportowej szczególnie dla obszarów zagrożonych powodzią i to w różnych skalach przestrzennych. Konieczne jest również regularna aktualizacja badań w związku z rozwojem sieci transportowej, zmianą liczy, rozmieszczenia i siły oddziaływania potencjałów ruchotwórczych oraz cech samego zagrożenia (np. granic obszaru, który może być nim objęty). Aktualne i szczegółowe wyniki pozwolą na sformułowane a następnie odpowiednio wczesne wdrożone procedur zarządzania przepływami transportowymi na poszczególnych poziomach przestrzennych. Dzięki zawczasu opracowanym zmianom w organizacji ruchu i ustaleniu kanałów informacyjnych, którymi zmiany te można odpowiednio wcześnie przekazać użytkownikom sieci drogowej, możliwe będzie szybsze doprowadzenie systemu transportowego do równowagi na nowym poziomie. Zaangażowania w tym względzie spodziewać się można ze strony m.in. operatorów Inteligentnych Systemów Transportowych zarówno na poziomie aglomeracyjnym jak i krajowym. Dysponują oni różnego rodzaju narzędziami, za pomocą których komunikować się mogą z podróżującymi, przekazując informacje o utrudnieniach na sieci drogowej i wskazówki dla ich uniknięcia w czasie rzeczywistym. Na poziomie regionalnym i krajowym daje to możliwość kształtowania pożądanych zachowań transportowych w sytuacjach kryzysowych. W skali lokalnej, poza opracowaniem strategii i planów operacyjnych na poziomie zarządców i organizatorów transportu, wskazane jest wykorzystanie uzyskanych rezultatów i metodyki badawczej dla opracowania programów informacyjnych dla mieszkańców terenów zagrożonych powodzią i obszarów w ich bezpośrednim sąsiedztwie. Na poziomie lokalnym, gdzie powódź bezpośrednio i natychmiastowo dotyka lokalnej społeczności, kluczowe są wyuczone zachowania odnoszące się wyboru ścieżki podróży, wyboru jej czasu czy środka transportu. Pozwoliłoby to na ograniczenie negatywnych skutków powodzi w zakresie zdrowia i życia ludności oraz podniosły efektywność działań służb ratowniczych w kontekście ochrony przeciwpowodziowej.

Mając na uwadze, że niemożliwym jest uniknięcie powodzi i prędzej czy później obejmie ona swoim oddziaływaniem, któryś z obszarów objętych symulacją, konieczne jest konsekwentne podejmowanie działań nastawionych na redukowanie liczby generatorów ruchu na tychże obszarach. W tym zakresie konieczne jest tworzenia konsekwentnego prawodawstwa warunkującego zagospodarowania terenów zagrożonych a następnie jego restrykcyjne przestyganie.

Cennym uzupełnieniem dla obowiązującej polityki w zakresie zarządzania terenami zagrożonymi powodzią, również ze względu na funkcjonowanie i rozwój infrastruktury drogowej, byłoby uwzględnienie sytuacji, w której ich granice ulegają poszerzeniu i obejmują obszary, których gospodarowanie w żaden sposób nie było dotychczas warunkowane takimi czynnikami. Globalne zmiany środowiska przyrodniczego i lokalne gospodarowanie człowieka może doprowadzić do sytuacji, kiedy granice wyznaczające tereny o 1% prawdopodobieństwa wystąpienia powodzi obejmą obszary chrakteryzujące się obecnie prawdopodobieństwem na poziomie 0,2%. Jako tereny uznawane w świadomości społecznej za całkowicie bezpieczne charakteryzują się one zgoła inną strukturą użytkowania ziemi, której przekształcenia idą w kierunku intensyfikacji zagospodarowania obarczonego wzrastającymi wartościami strat w sieci drogowej w wyniku potencjalnego zalania. Odpowiednio wcześnie uwzględnienie ewentualnego zagrożenia dałoby szansę na wypracowanie rozwiązań, które uszanowałby potencjał zagospodarowania transportowego tych terenów przy jednoczesnym uwzględnieniu zagrożenia. Pomocne w tym zakresie byłoby zapewne również uwzględnienie danych o zmianach zagospodarowania w ujęciu historycznym, które po zaimplementowaniu do procesu prognozowania przyszłych kierunków przemian, mogłyby zasygnalizować potrzebę wprowadzenia ewentualnych zmian do prawodawstwa, zapobiegającym niepożądanym praktykom.

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The monograph contains the results of research devoted to determining the vulnerability of passenger road transport in Poland by identifying the nature and scale of changes in transport accessibility and changes in the network traffic load in the event of a flood (with different probabilities of occurrence), conducted under the project number 2018/29/B/HS4/01020, financed by the National Science Center in Poland. In the course of the implementation of such formulated main goal of the study, an attempt was made to achieve a group of specific objectives of a cognitive, methodological and application character. The research was conducted mainly on the basis of data on the extent of flood risk areas in Poland and their development, as well as the road network and the development of its neighborhood. The publication may be of interest to researchers dealing with the geography of transport or – more broadly – with socio-economic geography and spatial management. It can also be helpful material for students of study programs that relate to the geography of transport, transport accessibility or spatial mobility in their curriculum. The content of the thesis covers issues that can be used by specialists in crisis management or road infrastructure management in crisis situations related to the occurrence of a flood.

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