

RIVER AND COASTAL FLOODING HAZARD IN THE VISTULA OUTLET, POLAND

Michael Nones^{1*}, Iwona Kuptel-Markiewicz², Emilia Wróbel ska³

Abstract

Flood risk at river-coast interfaces is an increasing concern under climate change and sea level rise, yet limited attention has been given to areas where riverine and coastal processes interact dynamically. This study assesses the river and coastal flood hazards in the Vistula River outlet, Poland, using multisource datasets handled via Geographical Information System (GIS) analysis. Flood hazard maps with return periods of 10, 100, and 500 years, which correspond to flood probabilities of 10%, 1%, and 0.2%, respectively, depending on the type of floods, were combined with detailed land cover and protected area datasets to quantify exposure to fluvial and coastal flooding. Results reveal that grassy vegetation and arable lands, covering more than two-thirds of the study area, are the most flood-prone land use categories, while built-up areas are particularly vulnerable in the event of levee breaches. Moreover, coastal flooding poses a greater threat than riverine flooding, both in extent and intensity, particularly affecting Natura 2000 sites located near the coast. These findings highlight the urgent need to integrate coastal and fluvial processes in hazard mapping and management frameworks in Poland, and to include compound flood considerations in national flood risk legislation. The approach presented here demonstrates the value of GIS-based assessments for identifying priority zones for flood mitigation, ecosystem conservation, and adaptive risk governance in deltaic and estuarine regions.

Received: 27 January, 2026

Revised: 31 March, 2026

Accepted: 15 May, 2026

Published: 25 July, 2026

^{1,2}*Department of Hydrology and Hydrodynamics, Institute of Geophysics Polish Academy of Sciences, 01-452 Warsaw, Poland.*

³*Faculty of Geography and Regional Studies, University of Warsaw, Uruski-Czetwertynski Palace, Krakowskie Przedmieście 30, Warsaw.*

***Corresponding author:**
mnones@igf.edu.pl

DOI: <https://doi.org/10.54552/v87i3.340>

Keywords:

Ecosystem services, Geographical Information Systems (GIS), River and coastal flooding, Vistula Outlet

1.0 INTRODUCTION

Flooding is among the most widespread and destructive natural hazards on Earth, affecting communities, economies, and ecosystems every year. Both riverine and coastal floods can devastate human settlements, disrupt essential infrastructure, and alter natural landscapes (Talbot *et al.*, 2018; Behrouz and Alimohammadi, 2023). The extent of flood-related damage varies widely across the globe, showing clear geographical patterns. In recent decades, parts of Asia and Europe have been particularly hard hit, facing repeated and often severe flood events (Alfieri *et al.*, 2014; Hamidifar and Nones, 2023).

Although flood science and management have advanced considerably, global flood losses continue to rise. This is largely due to a combination of factors, with more frequent climate extremes, expanding cities, changing land use, and population growth, especially in flood-prone areas (Hirabayashi *et al.*, 2021; Tellman *et al.*, 2021). Riverine floods are commonly triggered by intense, long-lasting rainfall or snowmelt, often accompanied by the failure of dams or levees. Coastal floods, on the other hand, are usually driven by storm surges, high tides, and the gradual rise of sea levels due to climate change. Recent studies have shown that these processes increasingly overlap, producing “compound flooding” events where river and coastal drivers act together or in sequence, amplifying the overall impact (Wahl *et al.*, 2015; Bevacqua *et al.*, 2019; Del-Rosal-Salido *et al.*, 2025). Low-lying estuarine areas, such as the Vistula outlet in Poland, are even more challenged by compound flood, also driven by a changing climate (Muñoz *et al.*, 2020; Zscheischler *et al.*, 2020; Brocchini *et al.*, 2025).

The delta of the Vistula River represents a coastal landform typical of semi-enclosed non-tidal seas such as the Baltic Sea (Cerkowniak and Ostrowski, 2019). Consequently, tidal oscillations play a negligible role in water-level variability, while storm surges and wind-driven setup are the dominant coastal drivers of extreme water levels. The term compound floods, or the related flood modelling approach, has not been used in relation to the Polish coast so far. The Polish classification of floods of various origins and territorial scope, in addition to floods in river basins caused by rainfall, meltwater or ice jams, also includes coastal floods caused by storm surges, which can occur throughout the year except for the months of May-July (Dobrowolski *et al.*, 2004). Storm surges themselves represent a recurrent flood-generating mechanism in Poland, occurring on average about once every 1.5 years. Strong winds can raise water levels in the Baltic Sea as well as in lakes and bays connected to it. Elevated sea levels may flood coastal cities and settlements. These wind-driven increases also hinder the outflow of river water and ice, leading to flooding at river mouths. When such storm surges coincide with snowmelt, heavy rainfall, or ice-jam floods within river catchments, the affected area can expand substantially, potentially resulting in extremely severe flooding (Dobrowolski *et al.*, 2004).

As reported in Cyberski *et al.* (2006), historical evidence confirms the high flood potential of the Vistula outlet, as it has experienced numerous major floods with substantial societal impact over nearly seven centuries, including ice jams, dike breaches, and storm-induced inundations. Recent major events

include, among others, the huge snowmelt- and rainfall-induced flood in 1924 (the most severe in the 20th century), then strong storm surge at the Vistula mouth in 1955, or the destructive flood in Gdańsk City (Vistula Outlet) caused by torrential rainfall in 2001. Due to high water levels on the Vistula River in May 2010, a flood alert was issued in many towns at the Vistula outlet and flood protection measures were taken (Maciejewski *et al.*, 2011). The damage caused by flooding is not just a matter of how extreme the event is, but also of where and whom it affects. Local geography, land use, and social vulnerability play decisive roles in determining the scale of losses. In response, modern flood management frameworks emphasise integration, combining prevention, protection, preparedness, and recovery within flexible and adaptive governance systems. These principles are at the heart of international initiatives like the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015). Such approaches aim not only to safeguard human lives and property, but also to preserve ecosystem services and the natural functions that support long-term resilience.

The current study uses Geographical Information Systems (GIS) to explore how both riverine and coastal floods affect the Vistula River outlet, the largest watercourse in Poland. The case study was selected as climate change and increasing human pressures are challenging delta regions at a very high pace (Zhang *et al.*, 2025), and new and holistic approaches are needed to reduce the impact of future floods on both human and natural compartments. By overlaying existing official flood hazard maps with detailed information on land use and protected areas, the analysis identifies which parts of the landscape are most exposed to floods of varying return periods. It is worth noticing that the current research considers riverine and coastal hazards separately, reflecting the current limitations of national flood mapping, as Polish regulations do not yet account for compound flooding (Ustawa, 2017; Rozporządzenie, 2022), which represents a growing risk in many deltaic and coastal regions across Europe (Ganguli *et al.*, 2020; Heinrich *et al.*, 2023).

2.0 MATERIALS AND METHODS

2.1 Case Study

One of the most prominent deltaic systems along the southern Baltic coast is the Vistula River outlet. It is situated in northern Poland, where the Vistula River, the longest river in the country, discharges into the Baltic Sea within the Gulf of Gdańsk. The considered delta is a coastal form typical for semi-enclosed nontidal seas, like the Baltic (Cerkowniak and Ostrowski, 2019). The specific study area (Figure 1) was derived from shapefile layers representing the boundaries of three physico-geographical regions located near the outlet (specifically Żuławy Wiślane, Mierzeja Wiślana, Wybrzeże Staropruskie) intersected with the layer representing catchment boundaries. The data were derived from several sources, i.e., the Polish Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) for catchments' boundaries, General Directorate for Environmental Protection (GDOŚ) for physico-geographical mesoregions, and the Central Institute of Geodesy and Cartography (GUGiK) for elevation and surface

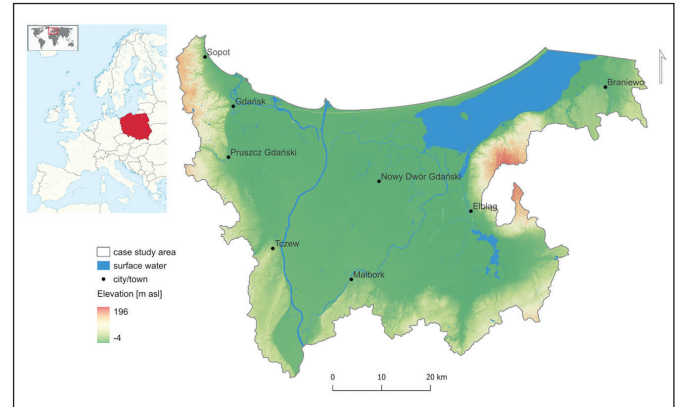


Figure 1: Case study area
(sources of the data: IMGW for catchments' boundaries, GDOŚ for physico-geographical mesoregions, GUGiK for elevation and surface waters, see Table A1)

waters. The data used for the studies, along with their provider and source, are given in the Appendix, Table A1.

The region is characterized by a temperate transitional climate influenced by both maritime and continental air masses. Mean annual air temperature ranges from about 7.5 to 9.0 °C, while annual precipitation typically varies between 550 and 650 mm, with a summer maximum (Staszek *et al.*, 2021). Winter conditions may include snow cover and episodic river ice formation, although their frequency has decreased in recent decades (Pawłowski, 2015; Pawłowski *et al.*, 2017).

Hydrologically, the Vistula drains a catchment of approximately 194,424 km² and has a mean annual discharge at the outlet of about 1080 m³/s, with strong seasonal variability driven by snowmelt and rainfall (Fal *et al.*, 2000). The outlet zone forms a river-sea interaction system, where fluvial processes intersect with marine dynamics, including storm surges and sea-level fluctuations and result in compound and cascading flood hazards (Cyberski *et al.*, 2006; Kundzewicz *et al.*, 2023; Green *et al.*, 2025).

The study area is about 3,443 km², and is predominantly lowland, with slight variations in elevation. Part of it lies below the sea level, and intersects with multiple canals and contains polders. According to the Central Statistical Office of Poland (GUS), the lowest point in the country is located within the study area, i.e., in Marzęcino, near the town of Nowy Dwór Gdański and has an altitude of -2.2 m below sea level. Several big and smaller cities, such as Gdańsk (489,000 citizens), Elbląg (112,000), Tczew (56,000), Malbork (37,000), Pruszcz Gdański (32,263), Braniewo (16,000), and Nowy Dwór Gdański (9,000), lie in this region. Despite extensive human modification, including river regulation, creating polders, land reclamation, and urbanisation, the area retains ecological functionality and landscape diversity. Several parts of the Vistula River outlet are protected under Natura 2000, national nature reserves, and landscape parks. The outlet is characterised by a combination of freshwater, brackish, and terrestrial ecosystems, including river channels, wetlands, reed beds, dunes, and shallow marine waters.

These environments are characterised by exceptionally high biological productivity and provide ecosystem services

from several types, i.e., supporting, provisioning, regulating, and cultural categories. For example, the environments present in the outlet provide an important regulating service that includes flood control and erosion protection through wetlands and floodplains in the estuary, which act as a natural retention (buffer), reducing flood peaks and stabilising banks, as well as reducing pollutants coming from the inland (Jabłońska *et al.*, 2020). Similarly, the area provides a provisioning service that includes the production of wild fish resources and serves as a spawning habitat (nursery function) for marine and river species (Liekens *et al.*, 2013; Koroza *et al.*, 2021; Krodzewska *et al.*, 2025).

2.2 Available Datasets

Land cover data are derived from the BDOT10k database created by GUGiK (Polish governmental institution) and regularly updated (Table A1). This database was preferred to CORINE data due to the need for high-resolution data. The majority of the study area is covered by grassy vegetation and arable land (69.13%), with a significant share of forested and wooded area and surface water (11.30% and 10.90%, respectively). Build-up area accounts for 5.25%, while other classes cover less than 2% (Figure 2).

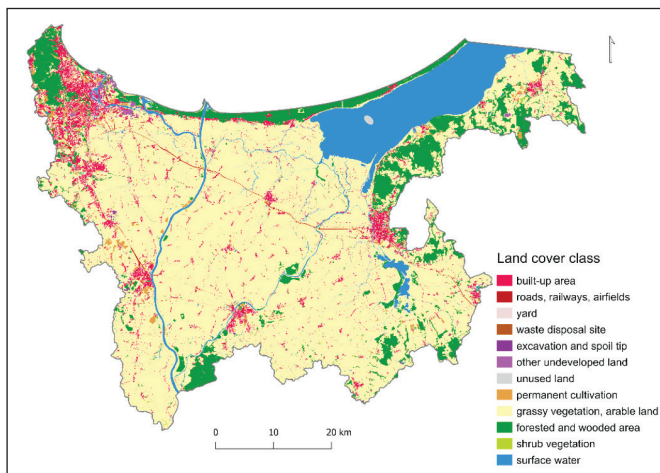


Figure 2: Mainland cover classes in the study area (source of the data: BDOT10k, see Table A1)

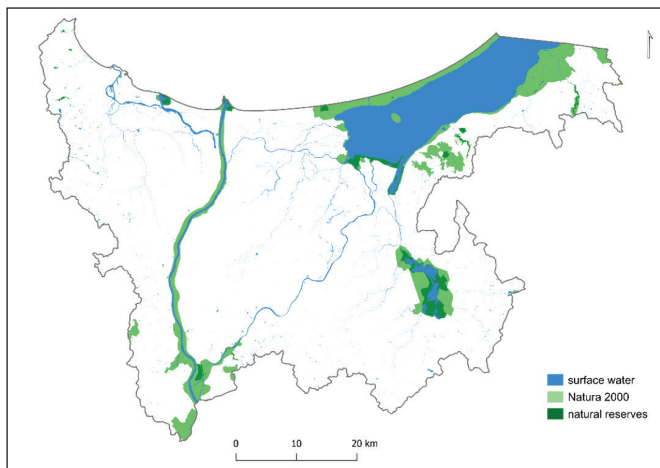


Figure 3: Protected areas (sources of the data: GDOŚ for protected areas; BDOT10k for surface waters, see Table A1)

According to Polish law, i.e., Act of 16 April 2004 on Environmental Protection – Ustawa z dnia 16 kwietnia 2004 r. o ochronie przyrody (Ustawa, 2004), there are nine types of protected areas in Poland. In the current analysis, only three of them are considered, namely national parks, natural reserves and Natura 2000 sites, as they have their equivalents in other European countries.

As, in the study region, there are no national parks, the analysis was conducted for only two types of protected areas, namely natural reserves and Natura 2000 sites. Specifically, 56 km² of the total area are covered by natural reserves, while almost 605 km² are designated as Natura 2000 sites (Figure 3). It is important to mention that, in Poland, the forms of nature protection are not mutually exclusive, meaning that a given area may be subject to several forms of protection at the same time.

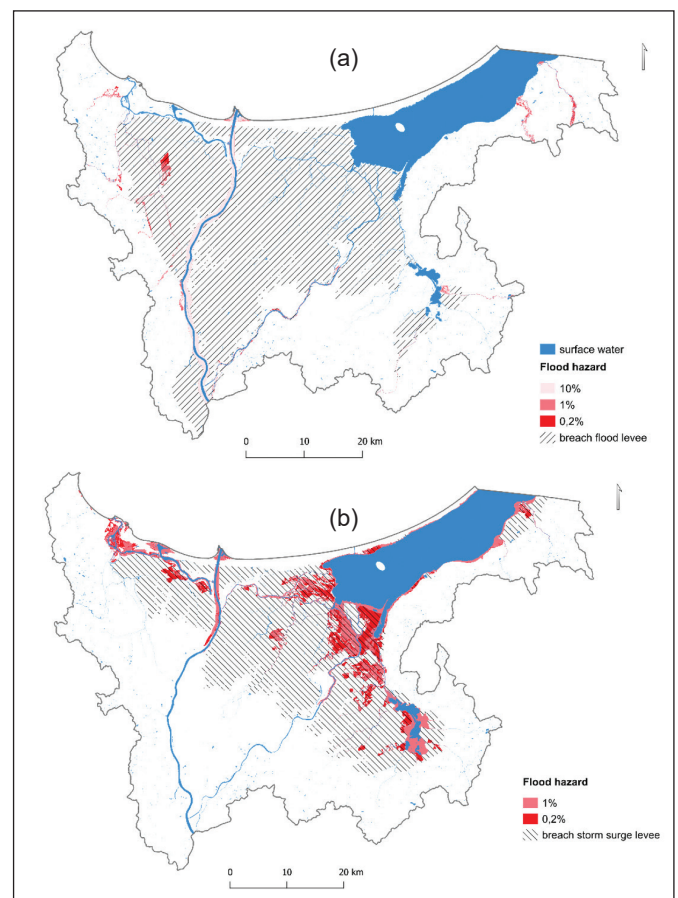


Figure 4: a) Fluvial flood hazard and b) coastal flood hazard zones (sources of the data: PGW Wody Polskie for flood hazard; BDOT10k for surface waters, see Table A1)

2.3 Flood Hazard Zones

In accordance with Polish (Water Law (Ustawa, 2017) and European laws (EU, 2007), Polish governmental institution responsible for the preparation of flood hazard maps, i.e. PGW Wody Polskie (State Water Management Polish Waters), is expected to prepare, release and update flood hazard maps for several flood scenarios, i.e. for fluvial (with 10%, 1% and 0,2% return probability) and coastal (1% and 0,2% probability) flooding as well as for two hypothetical situations: breach of the flood (river) levee and breach of the storm surge levee

determined for a flow with a probability of occurrence of 1% (Ustawa, 2017, Rozporządzenie, 2022). Figure 4 and Table 1 summarise the area at risk of river and coastal flooding for the individual return probability and different flood scenarios.

One can see that zones threatened by coastal flood hazard are predominant in the study area in the case of 100-year and 500-year floods (Figure 4a), affecting around 147 and 245 km², respectively, compared to the equivalent 85 and 93 km² affected by fluvial flood (Table 1). However, in the case of a levee failure, the area exposed to flooding is larger for a flood (river) levee breach (1327 km²) than for a storm levee breach (913 km²) (Figure 4b, Table 1).

Table 1: Area of flood hazard zones for different flood scenarios

Flood Type	Flood Scenario	Return Probability [%]	Area [km ²]
Fluvial	10-year flood	10	75.41
	100-year flood	1	85.41
	500-year flood	0.2	93.00
	breach of the flood levee	1	1326.80
Coastal	100-year flood	1	146.96
	500-year flood	0.2	244.63
	breach of the storm surge levee	1	913.41

3.0 RESULTS AND DISCUSSION

Information collected from multiple sources (Table A1) was handled in QGIS to derive the vulnerability of the study area to both fluvial and coastal floods.

3.1 Flood Hazard In Relation To Land Cover Classes

Focusing on land cover, it is possible to notice that grassy vegetation and arable land cover the majority of the study area (Figure 2), and, therefore, this class is also the most impacted by both fluvial (Table 2) and coastal (Table 3) flood hazard. In the tables, the area [km²] refers to the size of the area, while the area [%] refers to the percentage share of individual land cover classes in the total area of flood hazard zones of each

probability. From Table 2, one can see, as expected, that the lower the flood probability (i.e., the higher the return period), the larger the impact of flood on all classes apart from surface waters.

It is interesting to point out that, in the case of breach of river levees, inundation will have a significant impact on built-up areas, threatening an area of almost 40 km², which is much more than 1.14 km² in the case of a flood with a low probability of occurrence of 0.2%, i.e., once every 500 years. This justifies the need to maintain and ensure the proper technical condition of the current levees for safety reasons. At the same time, in light of climate change and a forecasted increase in extreme events (Kaczmarek, 2003), a constant revision of the existing structures, as well as the methods to calculate flood risk, should be ensured, in alignment with the European legislation (EU, 2007).

A similar behaviour is observable considering areas affected by coastal flood hazards, i.e., grassy vegetation and arable land, as well as other forested and wooded areas, are the most impacted regions (except surface waters), while build-up areas close to the coasts are also at risk (Table 3).

In this case, it is interesting to observe that the breach of storm surge levees will still have a significant impact on settlements (25 km²), which is significantly higher than in the case of the 100-year flood (around 3 km²) and the 500-year flood (7.4 km²). This calls for adequate protection measures, also implementing Nature based Solutions, as well as proper training of the population, to ensure safety during possible evacuations (Russo and Rindone, 2024). At the same time, the breach of such levees will cause significant flooding of grassy vegetation and arable land, which is estimated to cover an area of about 847 km², which represents 92.78% of the area flooded in this case.

3.2 Flood Hazard in Relation to Protected Areas

Protected areas play a major role in maintaining and/or improving ecosystems, and their presence and further development answer to the European Biodiversity Strategy for 2030 (environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en). Despite the availability of diverse ecosystem

Table 2: Impact of fluvial flood hazard on land cover classes

Land Cover Class	Probability						Breach of the Flood Levee	
	10%		1%		0.2%			
	Area [km²]	Area [%]	Area [km²]	Area [%]	Area [km²]	Area [%]	Area [km²]	Area [%]
Built-up area	0.10	0.13	0.72	0.84	1.14	1.23	39.77	3.00
Excavation and spoil tip	0.01	0.01	0.01	0.01	0.01	0.01	0.06	0.00
Forested and wooded area	4.12	5.47	5.21	6.10	5.75	6.19	20.94	1.58
Grassy vegetation and arable land	40.85	54.17	48.59	56.90	54.69	58.82	1207.50	91.14
Roads, railways and airfields	0.17	0.23	0.31	0.37	0.38	0.41	8.52	0.64
Other undeveloped land	0.01	0.02	0.06	0.07	0.07	0.07	3.27	0.25
Permanent cultivation	1.93	2.57	2.05	2.40	2.35	2.53	5.87	0.44
Shrub vegetation	0.86	1.14	0.88	1.03	0.91	0.98	1.83	0.14
Surface water	27.32	36.23	27.46	32.15	27.51	29.59	35.21	2.66
Unused land	0.02	0.02	0.02	0.03	0.03	0.03	0.08	0.01
Waste disposal site	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.01
Yard	0.01	0.01	0.08	0.10	0.14	0.15	1.73	0.13

Note that the area [km²] refers to the size of the area, while the area [%] refers to the percentage share of individual land cover classes in the total area of flood hazard zones of each probability

Table 3: Impact of coastal flood hazard on land cover classes

Land Cover Class	Probability				Breach of the Storm Surge Levee	
	1%		0.2%			
	Area [km ²]	Area [%]	Area [km ²]	Area [%]	Area [km ²]	Area [%]
Built-up area	2.97	2.02	7.38	3.02	25.20	2.76
Excavation and spoil tip	0.00	0.00	0.00	0.00	0.01	0.00
Forested and wooded area	12.68	8.63	17.06	6.97	16.42	1.80
Grassy vegetation and arable land	79.15	53.86	162.79	66.54	847.49	92.78
Roads, railways and airfields	0.57	0.39	1.77	0.72	6.32	0.69
Other undeveloped land	1.23	0.84	2.52	1.03	2.86	0.31
Permanent cultivation	1.66	1.13	2.09	0.85	4.21	0.46
Shrub vegetation	1.26	0.86	1.45	0.59	1.01	0.11
Surface water	44.19	30.07	45.01	18.40	8.72	0.95
Unused land	2.25	1.53	2.50	1.02	0.08	0.01
Waste disposal site	0.00	0.00	0.01	0.00	0.10	0.01
Yard	0.99	0.67	2.05	0.84	0.99	0.11

services models (Neumann *et al.*, 2022), the impact of climate change and the resulting flood risk have yet to be evaluated in detail in the Vistula Lagoon, although other examples across the Baltic Sea exist (Schernewski *et al.*, 2025).

The analysis of an impact of fluvial and coastal flood hazards on protected areas (natural reserves + Natura 2000) shown in Table 4 reveals that Natura 2000 areas are estimated to be more impacted by coastal floods than from fluvial ones, given that those areas are largely located close to the coasts and rather far from the Vistula River (Figures 5 and 6, green areas). It is worth noting here that floods may impact areas classified as both natural reserves and Natura 2000 sites, and

Table 4: Impact of fluvial and coastal flood hazard on protected areas

Flood Type	Protected Area Type	Area at Risk [km ²]			
		Probability			Breach of the Flood/ Storm Surge Levee*
		10%	1%	0.2%	
fluvial	natural reserve	1.80	2.72	3.12	9.73
	Natura 2000	39.54	42.02	43.92	42.11
	total	39.54	42.03	43.94	42.12
coastal	natural reserve	-	25.68	25.88	2.00
	Natura 2000	-	50.93	64.46	65.90
	total	-	50.94	64.46	65.90

*flood levee for fluvial floods and storm surge levee for coastal floods

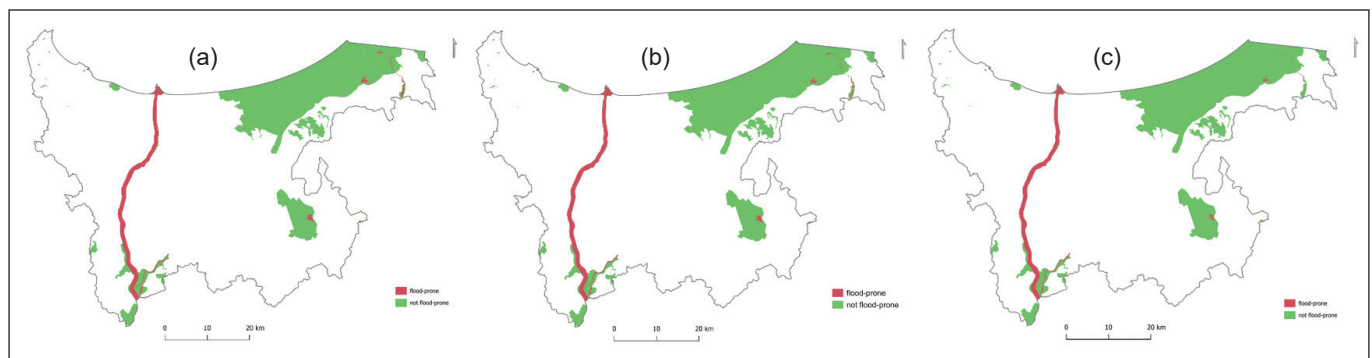


Figure 5: Protected areas within fluvial flood hazard zones characterised by a return probability of a) 0.2%, b) 1%, and c) 10%. Only small changes are visible in the upper right part of the study area

this implies that the total reported in Table 4 may differ from the sum of the two categories. As visible from Table 4 and Figure 5, areas at risk do not change significantly with the increase of flood hazard return period (i.e., decrease of probability), indicating that current levees protect the area rather well. On the other hand, changes in coastal flood risk led to quite significant changes in areas at risk (Table 4 and Figure 6), meaning

that this coastal region is more subject to coastal hazards due to its topography, as well as the nature of storm surge in the Baltic Sea (Zeidler, 1995; Pruszek and Zawadzka, 2005).

3.3 Legislative Limitations

As pointed out by Bevacqua *et al.* (2019), the definition of return period (or return probability) for compound flooding is far from being unique, as each definition brings different information that should be adapted to the case under study (Serinaldi, 2015). This points out a clear limitation in the practical application, as no agreement on what definition should be followed translates into a lack of a clear legislative background. The Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks, commonly known as the Floods Directive - FD (EU, 2007) requires Member States to implement flood risk management in recurring 6-year cycles (Nones, 2015).

As discussed in Del-Rosal-Salido *et al.* (2025), at the end of the second cycle of FD implementation, most EU countries updated their assessments (EU, 2021), and it seems that fluvial flooding would remain the primary concern in the future. However, in this second cycle, while the influence of climate change on flood risk assessments had been considered (Holguin, 2021), compound flooding had still not been properly considered, despite multiple evidence claims for its inclusion (Del-Rosal-Salido *et al.*, 2025).

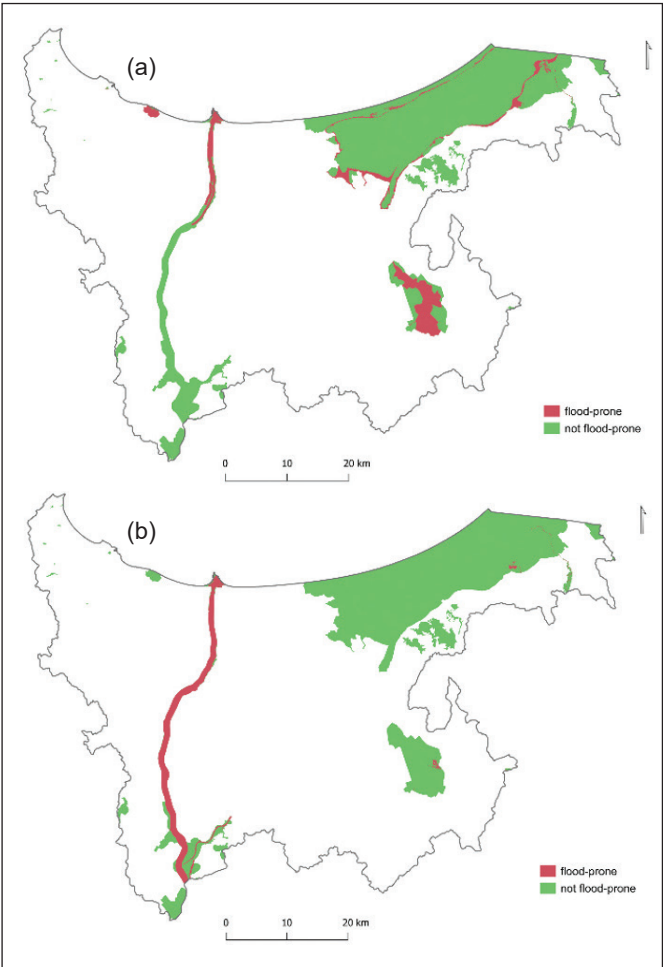


Figure 6: Protected areas within coastal flood hazard zones characterised by a return probability of a) 0.2% and b) 1%

4.0 CONCLUSIONS

The current study leveraged existing datasets to investigate the impact of fluvial and coastal floods on the Vistula River outlet analysis for different flood scenarios. The analysis is based on official flood maps, aiming to showcase the need to further develop science-based evidence on forming flood mechanisms that call for new approaches to compound flood mapping. The GIS-based results reveal marked differences in the spatial extent and intensity of exposure to the two types of flooding. Coastal flood hazard dominates both with respect to the land cover classes and protected areas for 100-year and 500-year flood scenarios.

Although built-up zones represent a relatively small fraction of the total land cover, they remain highly vulnerable, particularly in the case of levee breaches, both flood and surge storm levees, which underscores the need for continuous maintenance and upgrading of flood defence structures. Protected areas, especially those designated as Natura 2000 sites, are shown to be significantly exposed to coastal flooding, emphasising the necessity of integrating ecosystem-based adaptation strategies into flood risk management. This finding highlights the importance of aligning environmental protection objectives with disaster risk reduction policies to ensure the long-term resilience of both human and natural systems.

The study also identifies a critical limitation in the current Polish flood management framework, which treats fluvial and marine flooding as separate phenomena. This division hinders a comprehensive understanding of compound flooding processes that increasingly threaten coastal and deltaic environments under changing climatic conditions. Such a limitation is also visible at the European level, where only a few case studies point out the importance of compound flood risk management (Brocchini *et al.*, 2025; Del-Rosal-Salido *et al.*, 2025).

Overall, the present research calls for a more integrated river-coastal flood risk management approach that combines engineering, ecological, and governance perspectives. Future research should prioritise the inclusion of compound flood modelling, the development of early warning systems that consider multiple flood drivers, and the incorporation of ecosystem services into adaptive flood resilience planning.

ACKNOWLEDGEMENT

This work was partially funded by the project EcoC2S (Water4All 2023 Joint Transnational Call “Aquatic Ecosystem Services”, PCI2025-1) and by a subsidy from the Polish Ministry of Education and Science for the Institute of Geophysics Polish Academy of Sciences. EcoC2S has received funding from MICIU/AEI/10.13039/501100011033/UE, MUR - Ministry of Universities and Research, FCT - Fundação para a Ciência e a Tecnologia, NCBR - The National Centre for Research and Development in Poland and the European Union’s Horizon Europe Programme under the 2023 Joint Transnational Call of the European Partnership Water4All (Grant Agreement n°101060874). EcoC2S project website: <https://ecoc2s-water4all.dinamicambiental.es> ■

AUTHORS’ CONTRIBUTIONS

Michael Nones	Conceptualisation, study design, project management, supervision, writing review, editing, and final manuscript approval.
Iwona Kuptel-Markiewicz	Formal analysis, supervision, writing review, editing, and final manuscript approval.
Emilia Wróbelńska	Writing original draft, literature review, data visualisation and management, writing review, editing, and final manuscript approval.

REFERENCES

[1] Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., & Feyen, L. (2017). Global projections of river flood risk in a warmer world. *Earth's Future*, 5(2), 171–182. <https://doi.org/10.1002/2016EF000485>

[2] Behrouz, M., & Alimohammadi, S. (2025). Risk management and components' coordination assessment in the design of a composite riverine flood defence system. *International Journal of River Basin Management*, 23(1), 105–121. <https://doi.org/10.1080/15715124.2023.2249436>

[3] Bevacqua, E., Maraun, D., Voudoukas, M. I., Voukouvalas, E., Vrac, M., Mentaschi, L., & Widmann, M. (2019). Higher probability of compound flooding

- from precipitation and storm surge in Europe under anthropogenic climate change. *Science Advances*, 5(9), eaaw5531. <https://doi.org/10.1126/sciadv.aaw5531>
- [4] Brocchini, M., Marini, F., & Baldoni, A. (2025). Wave-current interactions within microtidal systems. *Coastal Engineering*. Advance online publication. <https://doi.org/10.1016/j.coastaleng.2025.104932>
- [5] Cerkowniak, G. R., & Ostrowski, R. (2020). Simple approach to long-term morphodynamics of the river delta applied to the Vistula River outlet. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 146(1). [https://doi.org/10.1061/\(ASCE\)WW.1943-5460.0000529](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000529)
- [6] Cyberski, J., Grześ, M., Gutry-Korycka, M., Nachlik, E., & Kundzewicz, Z. W. (2006). History of floods on the River Vistula. *Hydrological Sciences Journal*, 51(5), 799–817. <https://doi.org/10.1623/hysj.51.5.799>
- [7] Del-Rosal-Salido, J., Bermúdez, M., Ortega-Sánchez, M., Sanuy, M., Silva-Santana, M., & Jiménez, J. A. (2025). A composite index framework for compound flood risk assessment. *Communications Earth & Environment*, 6(1), Article 342. <https://doi.org/10.1038/s43247-025-02331-z>
- [8] Dobrowolski, A., Czarnecka, H., Ostrowski, J., & Zaniewska, M. (2004). Floods in Poland from 1946 to 2001: Origin, territorial extent and frequency. In *Proceedings of the Conference "Risks Caused by the Geodynamic Phenomena in Europe"* (Polish Geological Institute Special Papers No. 15, pp. 69–76).
- [9] European Commission. (2007). *Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks*. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0060>
- [10] European Commission. (2021). European overview: *Second preliminary flood risk assessments* (COM(2021) 970 final; SWD(2021) 970 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021SC0971>
- [11] Fal, B., Bogdanowicz, E., Czernuszenko, W., Dobrzyńska, I., & Koczyńska, A. (2000). *Przebiegi charakterystyczne głównych rzek Polski w latach 1951–1995 [Characteristic flows of the main rivers in Poland in the years 1951–1995]. Materiały Badawcze IMGW. Hydrologia i Oceanologia* (No. 26). Instytut Meteorologii i Gospodarki Wodnej.
- [12] Ganguli, P., Paprotny, D., Hasan, M., Güntner, A., & Merz, B. (2020). Projected changes in compound flood hazard from riverine and coastal floods in northwestern Europe. *Earth's Future*, 8(11), e2020EF001752. <https://doi.org/10.1029/2020EF001752>
- [13] Green, J., Haigh, I. D., Quinn, N., Neal, J., Wahl, T., Wood, M., Eilander, D., de Ruiter, M., Ward, P., & Camus, P. (2025). A comprehensive review of compound flooding literature with a focus on coastal and estuarine regions. *Natural Hazards and Earth System Sciences*, 25, 747–816. <https://doi.org/10.5194/nhess-25-747-2025>
- [14] Hamidifar, H., & Nones, M. (2023). Spatiotemporal variations of riverine flood fatalities: A 70-year global to regional perspective. *River*, 2(2), 222–238. <https://doi.org/10.1002/rvr2.45>
- [15] Heinrich, P., Hagemann, S., Weisse, R., & Gaslikova, L. (2023). Changes in compound flood event frequency in northern and central Europe under climate change. *Frontiers in Climate*, 5, Article 1227613. <https://doi.org/10.3389/fclim.2023.1227613>
- [16] Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, 3(9), 816–821. <https://doi.org/10.1038/nclimate1911>
- [17] Holguín, N., Mugica, A., & Ukar, O. (2021). How is climate change included in the implementation of the European Floods Directive? Analysis of the methodological approaches of different countries. *Water*, 13(11), Article 1490. <https://doi.org/10.3390/w13111490>
- [18] Jabłońska, E., Wiśniewska, M., Marcinkowski, P., Grygoruk, M., Walton, C. R., Zak, D., & Kotowski, W. (2020). Catchment-scale analysis reveals high cost-effectiveness of wetland buffer zones as a remedy to non-point nutrient pollution in north-eastern Poland. *Water*, 12(3), Article 629. <https://doi.org/10.3390/w12030629>
- [19] Kaczmarek, Z. (2003). The impact of climate variability on flood risk in Poland. *Risk Analysis*, 23(3), 559–566. <https://doi.org/10.1111/1539-6924.00336>
- [20] Koroza, A., Węslawski, J. M., Piwowarczyk, J., & Zieliński, T. (2021). *Rozpoznanie i ocena usług ekosystemowych: Studium przypadku istotnych usług ekosystemów morskich* [Recognizing and assessing ecosystem services: A case study of essential marine ecosystem services]. Instytut Oceanologii Polskiej Akademii Nauk.
- [21] Krodzewska, M., Spyra, A., Koczorowska, A., Łozowski, B., Czerniawski, R., Sługocki, Ł., & Cieplik, A. (2025). Exploring a large European river: Unraveling the spatial distribution and diversity of benthic invertebrates along the Vistula River (Poland). *Ecohydrology & Hydrobiology*. Advance online publication. <https://doi.org/10.1016/j.ecohyd.2025.100681>
- [22] Kundzewicz, Z. W., Januchta-Szostak, A., Nachlik, E., Piskwar, I., & Zaleski, J. (2023). Challenges for flood risk reduction in Poland's changing climate. *Water*, 15(16), Article 2912. <https://doi.org/10.3390/w15162912>
- [23] Liekens, I., Broekx, S., & De Nocker, L. (2013). *Manual for the valuation of ecosystem services in estuaries*. VITO.
- [24] Maciejewski, M., Ostojski, M. S., & Walczykiewicz, T. (Eds.). (2011). *Dorzecze Wisły: Monografia powodzi: Maj-czerwiec 2010* [Vistula River basin: Flood monograph: May-June 2010]. Instytut Meteorologii i Gospodarki Wodnej.

- [25] Muñoz, D. F., Moftakhari, H., & Moradkhani, H. (2020). Compound effects of flood drivers and wetland elevation correction on coastal flood hazard assessment. *Water Resources Research*, 56(7), e2020WR027544. <https://doi.org/10.1029/2020WR027544>
- [26] Neumann, T., Radtke, H., Cahill, B., Schmidt, M., & Rehder, G. (2022). Non-Redfieldian carbon model for the Baltic Sea (ERGOM version 1.2): Implementation and budget estimates. *Geoscientific Model Development*, 15(22), 8473–8540. <https://doi.org/10.5194/gmd-15-8473-2022>
- [27] Nones, M. (2015). Implementation of the Floods Directive in selected EU member states. *Water and Environment Journal*, 29(3), 412–418. <https://doi.org/10.1111/wej.12129>
- [28] Pawłowski, B. (2015). Determinants of change in the duration of ice phenomena on the Vistula River in Toruń. *Journal of Hydrology and Hydromechanics*, 63(2), 145–153. <https://doi.org/10.1515/johh-2015-0017>
- [29] Pawłowski, B., Gorączko, M., & Szczerbińska, A. (2017). Zjawiska lodowe w rzekach Polski [Ice phenomena on Polish rivers]. In P. Jokiel, W. Marszelewski, & J. Pociask-Karteczka (Eds.), *Hydrologia Polski*. Wydawnictwo Naukowe PWN.
- [30] Pruszek, Z., & Zawadzka, E. (2005). Vulnerability of Poland's coast to sea-level rise. *Coastal Engineering Journal*, 47(2-3), 131–155. <https://doi.org/10.1142/S0578563405001197>
- [31] Regulation of the Minister of Infrastructure of October 18, 2022, on the adoption of the Flood Risk Management Plan for the Vistula River Basin District. (2022). *Journal of Laws of 2022*, Item 2739 (Poland). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20220002739/O/D20222739.pdf>
- [32] Russo, F., & Rindone, C. (2024). Methods for risk reduction: Training and exercises to pursue the planned evacuation. *Sustainability*, 16(4), Article 1474. <https://doi.org/10.3390/su16041474>
- [33] Schernewski, G., Neumann, T., Piehl, S., & Swer, N. M. (2025). Ecosystem model-based valuation of ecosystem services in a Baltic lagoon: Long-term human technical interventions and short-term variability. *Environments*, 12(2), Article 35. <https://doi.org/10.3390/environments12020035>
- [34] Serinaldi, F. (2015). Dismissing return periods! *Stochastic Environmental Research and Risk Assessment*, 29(4), 1179–1189. <https://doi.org/10.1007/s00477-014-0916-1>
- [35] Staszek, W., Kistowski, M., Niecikowski, K., Wiśniewski, P., Borzyszkowski, J., & Grzegorzczak, I. (2021). Pobrzeże Gdańskie (313.5) [Gdańsk Coast (313.5)]. In A. Richling, J. Solon, A. Macias, J. Balon, J. Borzyszkowski, & M. Kistowski (Eds.), *Regionalna geografia fizyczna Polski* (pp. 96–106). Bogucki Wydawnictwo Naukowe.
- [36] Talbot, C. J., Bennett, E. M., Cassell, K., Hanes, D. M., Minor, E. C., Paerl, H. W., Xenopoulos, M. A., & others. (2018). The impact of flooding on aquatic ecosystem services. *Biogeochemistry*, 141(3), 439–461. <https://doi.org/10.1007/s10533-018-0449-7>
- [37] Tellman, B., Sullivan, J. A., Kuhn, C., Kettner, A. J., Doyle, C. S., Brakenridge, G. R., Slayback, D. A., & others. (2021). Satellite imaging reveals increased proportion of population exposed to floods. *Nature*, 596(7870), 80–86. <https://doi.org/10.1038/s41586-021-03695-w>
- [38] United Nations Office for Disaster Risk Reduction. (2015). *Sendai framework for disaster risk reduction 2015-2030*. <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>
- [39] Act of April 16, 2004, on Nature Protection. (2004). *Journal of Laws of 2004*, No. 92, Item 880 (Poland). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20040920880/O/D20040880.pdf>
- [40] Water Law Act of July 20, 2017. (2021). *Journal of Laws of 2021*, Item 2233 (Poland). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20210002233/U/D20212233Lj.pdf>
- [41] Wahl, T., Jain, S., Bender, J., Meyers, S. D., & Luther, M. E. (2015). Increasing risk of compound flooding from storm surge and rainfall for major U.S. cities. *Nature Climate Change*, 5(12), 1093–1097. <https://doi.org/10.1038/nclimate2736>
- [42] Zeidler, R. B. (1995). Vulnerability of Poland's coastal areas to sea level rise. *Journal of Coastal Research*, 99–109. <https://www.jstor.org/stable/25736032>
- [43] Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C. M., Horton, R. M., Vignotto, E., & others. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, 1(7), 333–347. <https://doi.org/10.1038/s43017-020-0060-z>
- [44] Zhang, M., Nicholls, R. J., Wen, J., AghaKouchak, A., Bouma, T. J., Darby, S. E., Dai, Z., & others. (2025). Growing compound-flood risk, driven by both climate change and land subsidence, challenges flood risk reduction in major delta cities. *One Earth*. Advance online publication. <https://doi.org/10.1016/j.oneear.2025.101489>

APPENDIX

Table A1: Datasets and sources

Data available	Data provider	Source
Catchment boundaries	Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy (IMGW)	https://drive.google.com/drive/folders/1UNI5U3zuprYBdyXdbv0VUtH3Ei_6iL4R?usp=sharing
Digital Terrain Model (DTM) (Numeryczny Model Terenu (NMT) – spatial resolution 5m)	Główny Instytut Geodezji i Kartografii (GUGiK), geoportal.gov.pl – Polish governmental institution	Geoportal.gov.pl – website with links to WFS: https://www.geoportal.gov.pl/pl/dane/numeryczny-model-terenu-nmt/WFS: https://mapy.geoportal.gov.pl/wss/service/PZGIK/NumerycznyModelTerenuEVRF2007/WFS/Skorowidze
Flood hazard (Mapy Zagrożenia Powodziowego (MZP))	PGW Wody Polskie - Polish governmental institution	"Wody Polskie – Baza WMS" plug in for QGIS Otwarte Dane website: https://dane.gov.pl/pl/dataset/2178,mapa-zagrozenia-powodziowego-mzp
Flood risk (Mapy Ryzyka powodziowego (MRP))	PGW Wody Polskie - Polish governmental institution	"Wody Polskie – Baza WMS" plug in for QGIS
Land Cover (BDOT10k) (Baza danych obiektów topograficznych – BDOT 10k)	Główny Instytut Geodezji i Kartografii (GUGiK) – Polish governmental institution	"Pobieracz danych GUGiK" plug in for QGIS
Land Cover (CLC) (Corine Land Cover 2018)	European Environment Agency (EEA), Copernicus Land Monitoring Service (CLMS)	Copernicus Land Monitoring Service (CLMS): https://land.copernicus.eu/en/products/corine-land-cover/clc2018#download
Hydrotechnical infrastructure* (BDOT 10k)	Główny Instytut Geodezji i Kartografii (GUGiK) – Polish governmental institution	"Pobieracz danych GUGiK" plug in for QGIS
Critical/important infrastructure**	Główny Instytut Geodezji i Kartografii (GUGiK) – Polish governmental institution	"Pobieracz danych GUGiK" plug in for QGIS
Protected areas	Generalna Dyrekcja Ochrony Środowiska (GDOŚ) – Polish governmental institution	GDOŚ website: https://www.gov.pl/web/gdos/dostep-do-danych-geoprzestrzennych
Physico-geographical mesoregions of Poland	Generalna Dyrekcja Ochrony Środowiska (GDOŚ) – Polish governmental institution	GDOŚ website: https://www.gov.pl/web/gdos/dostep-do-danych-geoprzestrzennych
Hydrological and meteorological stations (located in the case study area or nearby)	Instytut Meteorologii i Gospodarki Wodnej (IMGW) - Polish governmental institution	IMGW website: https://hydro.imgw.pl/#!/map?lo=18.9356&la=54.3364&zo=11&fst=toLevels
Meteorological data from stations (located in the case study area or nearby)	Instytut Meteorologii i Gospodarki Wodnej (IMGW) - Polish governmental institution	IMGW website: https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/dane_meteorologiczne/

* lock/sluice gates, weirs, dams, breakwaters, groynes, bank reinforcements, flood embankments/ levees or dykes

** bridges, roads, railways, power lines, pipelines, deep wells, buildings, etc.

PROFILES



MICHAEL NONES is an Associate Professor in the Hydrology and Hydrodynamics Department at the Institute of Geophysics, Polish Academy of Sciences in Warsaw, Poland. He holds a habilitation in Earth Sciences, and a PhD in Civil and Environmental Engineering from the University of Padova, Italy. He currently works and leads projects on fluvial morphodynamics and geomorphology, combining numerical modelling with remote sensing, to understand how climate and human-driven changes influence river systems' dynamics and water quality, specifically sediment transport. He published more than 50 peer-reviewed articles on the topic, and is currently the Editor in Chief of the International Journal of River Basin Management.

Email address: mnonnes@igf.edu.pl



IWONA KUPTTEL-MARKIEWICZ is an Associate Professor at the Institute of Geophysics of the Polish Academy of Sciences (IGF PAS) in Warsaw, Poland, where she works in the Department of Hydrology and Hydrodynamics. She holds a habilitation degree (2023) and a PhD (2009) in Earth Sciences in the discipline of geophysics, as well as a M.Sc. in Mathematics from the Warsaw University of Technology. Her research focuses on hydrological extremes, particularly the statistical and stochastic modelling of floods, droughts, and extreme precipitation, as well as risk assessment and the influence of anthropogenic factors on hydrological regimes. She is actively involved in international research collaborations and projects, including Horizon Europe and COST Action initiatives, and has contributed to advancing modern statistical approaches in hydrology. She has authored and co-authored numerous peer-reviewed publications in leading international journals. She is a member of the International Association of Hydrological Sciences (IAHS), including the International Commission on Statistical Hydrology.

Email address: iwonamar@igf.edu.pl



EMILIA WRÓBELSKA is a Master's student at the University of Warsaw, pursuing a degree in Geography with a specialisation in Hydrology and Climatology within the Inter-faculty Individual Studies in Mathematics and Natural Sciences (MISMaP). She holds a bachelor's degree in Geography from the same institution. Her research experience includes a scientific internship at the Institute of Geophysics of the Polish Academy of Sciences, as well as participation in student research projects focused on hydrology, including the functioning of streams in urban areas.

Email address: emilia.wrobelska@gmail.com