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**The occurrence and causes of floods in Polish lands from
the 11th to 18th centuries**

Doctoral thesis completed at the Department of Meteorology and Climatology
under the supervision

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I am dedicating this thesis to my mother, Akram, for her sacrifices, kindness, and endless support throughout my life. Also, I dedicate this thesis to my wife, Ghazal, for her love and encouragement and to my brothers, Saber and Farhad.

I hope the sacrifices you've endured to support my dream will be rewarded with abundant opportunities for happiness and achievement in the days ahead.

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List of scientific publications related to the Ph.D. project

No.	Title of paper and authors (DOI)	Year <i>journal name</i> (ISSN)	Impact factor	Points (MNiSW)
P1	The frequency, intensity, and origin of floods in Poland in the 11 th –15 th centuries based on documentary evidence Babak Ghazi* , Rajmund Przybylak, Piotr Oliński, Katarzyna Bogdańska, Aleksandra Pospieszńska (https://doi.org/10.1016/j.jhydrol.2023.129778)	2023 <i>Journal of Hydrology</i> (0022-1694)	6.4	140
P2	An assessment of flood occurrences in Poland in the 16 th century Babak Ghazi , Rajmund Przybylak, Piotr Oliński, Waldemar Chorażyczewski, Aleksandra Pospieszńska (https://doi.org/10.1016/j.ejrh.2023.101597)	2023 <i>Journal of Hydrology: Regional Studies</i> (2214-5818)	4.7	100
P3	A comprehensive study of floods in Poland in the 17 th –18 th centuries Babak Ghazi , Rajmund Przybylak, Piotr Oliński, Michał Targowski, Janusz Filipiak, Aleksandra Pospieszńska (https://doi.org/10.1016/j.ejrh.2024.101796)	2024 <i>Journal of Hydrology: Regional Studies</i> (2214-5818)	4.7	100
P4	Flood occurrences and characteristics in Poland in the last millennium Babak Ghazi , Rajmund Przybylak, Piotr Oliński, Aleksandra Pospieszńska	2024 Submitted to <i>Scientific Reports</i> (2045-2322)	4.6	140
Sum			20.4	480

***Babak Ghazi** is the corresponding and first author for all papers.

List of conference publications (presentations) related to the Ph.D. project

No.	Title of presentation (publication)	Conference Name	Type of presentation
1	Reconstruction of floods in Poland in the last 1000 years	European Meteorological Society, Annual Meeting Barcelona, Spain, 2–6 September 2024	Oral Presentation (accepted)
2	Projection of climate change impact on climate classification and occurrence of extreme events in Poland	35th International Geographical Congress, Dublin, Ireland, 24–30 August 2024	Oral Presentation (accepted)
3	Reconstruction of floods in Poland in the pre-instrumental period (1001–1800)	European Geosciences Union, Annual Meeting, Vienna, Austria, 14–19 April 2024	Oral presentation
4	Documentary evidence of past floods in Poland in the 11th–15th centuries	European Meteorological Society, Annual Meeting Bratislava, Slovakia, 3–8 September 2023	Oral presentation
5	Estimation of droughts and flood occurrences in central Poland under climate change scenarios	European Meteorological Society, Annual Meeting, Bratislava, Slovakia, 3–8 September 2023	Poster presentation
6	Impact of climate change on temperature and precipitation in Toruń, Poland, based on CMIP6 under SSP scenarios	European Geosciences Union, Annual Meeting, Vienna, Austria, 23–28 April 2023	Oral presentation
7	The frequency, scale, and origin of floods in Poland in the 12th–15th centuries based on historical sources	Weather and climate - past, present, future, Jagiellonian University, Krakow, Poland 21–23 September 2022	Oral presentation

Other scientific publications

No.	Title of paper	Year journal name (ISSN)	Impact factor
1	Evaluation of Climatological Precipitation Datasets and Their Hydrological Application in the Hablehroud Watershed, Iran (https://doi.org/10.3390/w16071028)	2024 <i>Water</i> (2073-4441)	3.4
2	Projection of climate change impacts on extreme temperature and precipitation in Central Poland, (https://doi.org/10.1038/s41598-023-46199-5)	2023 <i>Scientific Reports</i> (2045-2322)	4.6
3	Projection of future meteorological droughts in Lake Urmia Basin, Iran (https://doi.org/10.3390/w15081558)	2023 <i>Water</i> (2073-4441)	3.4
4	A proposed approach towards quantifying the resilience of water systems to the potential climate change in the Lali Region, Southwest Iran (https://doi.org/10.3390/cli10110182)	2022 <i>Climate</i> (2225-1154)	3.7
5	Estimation of Tasuj aquifer response to main meteorological parameter variations under Shared Socioeconomic Pathways scenarios (https://doi.org/10.1007/s00704-022-04025-4)	2022 <i>Theoretical and Applied Climatology</i> (1434-4483)	3.17
6	Projection of temperature and precipitation under climate change in Tabriz, Iran (https://doi.org/10.1007/s12517-022-09848-z)	2022 <i>Arabian Journal of Geosciences</i> (1866-7511)	-
7	Response of the Shabestar Plain aquifer to climate-change scenarios through statistical and hybrid soft computing techniques (https://doi.org/10.1016/j.gsd.2021.100649)	2021 <i>Groundwater for Sustainable Development</i> (2352-801X)	5.9
8	Assessment of probable groundwater changes under representative concentration pathway (RCP) scenarios through the wavelet–GEP model (https://doi.org/10.1007/s12665-021-09746-9)	2021 <i>Environmental Earth Sciences</i> (1866-6280)	2.8
9	Predicting groundwater level fluctuations under climate change scenarios for Tasuj plain, Iran (https://doi.org/10.1007/s12517-021-06508-6)	2021 <i>Arabian Journal of Geosciences</i> (1866-7511)	-

General Statement

This thesis is part of a National Science Centre, Poland project (2020/37/B/ST10/00710) entitled “The occurrence of extreme weather, climate and water events in Poland from the 11th to 18th centuries in the light of multiproxy data.” The thesis is a combination of several papers (three published papers and one under review). All results presented in these papers are achieved based on four databases for flood occurrences in Poland.

Each database is based on various documentary evidence from historical sources and contains detailed and valuable information (location, time, duration, and the author’s indexation for intensity and origin of the floods) about flood occurrences in Poland. Three databases are created for sub-periods and one updated database has been created for the full period, i.e.:

- 11th–15th centuries (<https://doi.org/10.18150/WD18XJ>)
- 16th century (<https://doi.org/10.18150/T3RXRI>)
- 17th–18th centuries (<https://doi.org/10.18150/VLPAFG>)
- 11th–18th centuries (<https://doi.org/10.18150/VLTV9>).

The first paper [P1] is entitled “The frequency, intensity, and origin of floods in Poland in the 11th–15th centuries based on documentary evidence” and focuses on the evaluation of floods in the medieval period (11th–15th centuries) in Poland. Generally, only a few studies in Europe have covered the medieval period, and this research is one of the most comprehensive studies of flood history in this period. The second paper [P2], entitled “An assessment of flood occurrences in Poland in the 16th century,” specifically assessed floods in the 16th century in Poland, because various studies confirmed several extreme and disastrous flood occurrences in Central Europe in the 16th century. To complete the research on floods in Poland before the instrumental period (19th century), the last part of the research [P3] was carried out, focusing on the 17th–18th centuries and entitled “A comprehensive study of floods in Poland in the 17th–18th centuries.” In all of these studies, results were compared with some available literature for Poland and other Central Europe countries to provide a clear picture of how our results differed from those of previous studies. Although all of the mentioned studies investigated the history of floods in Poland, in terms of methodology and results section, based on the availability of sources and information in the weather notes, there are more detailed outputs. For example, in the study of floods in the 16th century [P2], there is a comparison (see Table 3 in the paper) of the main cause of floods in Poland against those of the main rivers in Austria (the Salzach and Traun rivers), Czechia (the Vltava, Elbe, and Ohře rivers), and Germany (the Elbe and Oder rivers) and Sweden. This comparison was not possible for the first paper, due to the lack of

detailed information for the medieval period. The results and discussions presented in **P3** are among the most comprehensive and detailed for flood history in Europe. In this paper, the frequency of floods in Poland is compared with six other studies for Poland. In addition, flood-rich periods and months/seasons of flood occurrences were retrieved for floods in Poland in the 17th–18th centuries. Another result only provided in this paper was a comprehensive comparison of flood frequency in the two rivers Vistula and Oder in Poland compared with the Danube, Dyje, Morava, Vltava, Elbe, Inn, Main, and Norrström rivers.

After publishing these papers, it was noted that there lacked any study comparing historical floods from the pre-industrial period (before the 19th century) with those after this period (19th–20th centuries). Thus, a new study [**P4**] with a focus on the history of floods in the last millennium entitled “Flood occurrences and characteristics in Poland in the last millennium” was undertaken to fill this gap. I believe that this study is one of the most comprehensive and detailed studies of historical floods in Central Europe. The study covers 1000 years of flood frequency in Poland with details for each sub-period. In addition, the frequency of floods for each main region of Poland and for major river basins of Poland in each sub-period are also presented. Another important part that was investigated in this research was the detection of statistical trends for floods and their extremes based on the Mann–Kendall tests. Moreover, the places (cities) where flood frequency was greater than other places were introduced in the last paper [**P4**].

An important fact that distinguishes this thesis from previous ones is that the results presented here were achieved in collaboration with a group of experts including historians, climatologists, and a hydrologist, and there is no such complete perspective in most previous studies for Europe.

It is worth mentioning that all databases and papers are open-access and freely available to the public.

To summarize, this thesis provides a summary and main results of the mentioned papers; however, it is recommended to read the papers in Appendix 2 for the detailed analyses they provide.

Abstract

In the era of global warming, in which extreme events are great threats to human society and the environment, the public is concerned about the possible consequences of these events. Throughout history, due to their catastrophic consequences, floods have affected human societies many times. Therefore, floods have been the main subject of great numbers of studies globally. Nevertheless, the lack of a sufficient and reliable dataset for floods before the industrial period (i.e. from around the mid-19th century) has limited studies of this topic. Therefore, documentary evidence, as a reliable source, served a significant part in the development of research for flood studies before the 19th century. This documentary evidence was used to establish four extensive databases detailing historical floods in Poland from 1001 to 1800. In addition, floods that occurred from 1801 to 2000 in Poland were compiled from available published literature on the subject to compare with the frequency of floods in 1001–1800. The databases of floods in the 11th–18th and information on flood frequency in the 19th–20th centuries were used to deeply investigate flood frequency, intensity, and origins in Poland. The results demonstrated the occurrence of 1,252 floods in 1001–1800 and 428 floods in 1801–2000 within the area of Poland. The most flood-prone period was the 18th century (356, 28%) and the least frequent period was the 11th–15th centuries (210, 17%). Among the three river basins of Poland (i.e., Oder River, Vistula River, and Baltic Coast rivers basin), floods were most abundant in the Oder River basin (671, 55%) and then Vistula River basin (522, 43%). The order of flood frequencies among the main regions of Poland was Silesia (553, 43%), followed by Baltic Coast and Pomerania (289, 23%), Lesser Poland (212, 17%), Greater Poland (109, 8%), Masovia (53, 4%), and Masuria-Podlasie (11, 1%). For 46 (4%) records, based on information in weather notes, there is no information about the exact region of floods (for which the miscellaneous category “Poland” was applied). The majority of floods occurred in the summer (46%), with fewer occurring in the autumn (8%). The classification of flood intensity revealed that, based on the Brázdil et al. (2006) classification, the largest category of floods (33% of all occurrences) was “above-average, or supra-regional flood,” whereas “extraordinary” floods (70%) were the most classified category for floods based on the Barriendos and Coeur (2004) classification. Moreover, rain was the leading cause of floods in Poland (44%) based on the Lambor (1954) classification. In general, by employing the Mann–Kendall test analysis, it was indicated that flood frequency in Poland decreased significantly ($p\text{-value} < 0.05$) between 1501 and 2000. On the other hand, positive trends were observed in the sub-periods 1501–1800 and 1801–2000, with a statistically significant trend only for 1801–2000.

Summary (Polish)

W dobie globalnego ocieplenia, w którym ekstremalne zjawiska stanowią ogromne zagrożenie dla społeczeństwa i środowiska, opinia publiczna jest zaniepokojona możliwymi konsekwencjami tych wydarzeń. Na przestrzeni dziejów, ze względu na swoje katastrofalne skutki, powodzie wielokrotnie dotyczyły ludzkie społeczności. Dlatego też stały się one głównym przedmiotem licznych badań na całym świecie. Niemniej jednak brak wystarczających i wiarygodnych danych dotyczących powodzi sprzed epoki przemysłowej (tj. sprzed ok. połowy XIX w.) utrudniał badania nad tym tematem. W związku z tym rozlicznego rodzaju źródła historyczne (ang. documentary evidence), sprawdzone pod względem wiarygodności zawartej w nich informacji, odegrały znaczącą rolę w rozwoju badań nad powodziami przed XIX wiekiem.

W niniejszej pracy zostały one wykorzystane do utworzenia czterech obszernych baz danych zawierających szczegółowe informacje o historycznych powodziach na ziemiach polskich w latach 1001–1800. Ponadto, z dostępnej opublikowanej literatury przedmiotu zebrano dane o powodziach, które miały miejsce w Polsce w latach 1801–2000, w celu porównania ich z częstością powodzi w latach 1001–1800. Wszystkie ww. bazy danych o występowaniu powodzi w okresie ostatniego tysiąclecia w Polsce posłużyły do dogłębnego zbadania częstości, intensywności i genezy powodzi na tym obszarze. Przeprowadzona analiza statystyczna wykazała wystąpienie 1252 powodzi w latach 1001–1800 oraz 428 powodzi w latach 1801–2000 na obszarze Polski. Najbardziej obfitym w powodzie był XVIII wiek (356, 28%), a najmniej ich wystąpiło w okresie XI–XV w. (210, 17%). Spośród analizowanych trzech głównych dorzeczy Polski (tj. dorzecza Odry, Wisły i rzek Pobrzeża Bałtyckiego) powodzie występowały najczęściej w dorzeczu Odry (671, 55%), a następnie w dorzeczu Wisły (522, 43%). W ujęciu regionalnym najwięcej powodzi zanotowano na Śląsku (553, 43%), a dużo mniej w regionach: Wybrzeża Bałtyckiego i Pomorza (289, 23%), Małopolski (212, 17%), Wielkopolski (109, 8%), Mazowsza (53, 4%) oraz Mazur i Podlasia (11, 1%). W przypadku 46 (4%) zapisów pogodowych informujących o wystąpieniu powodzi brak jest informacji o miejscu jej wystąpienia, dlatego w tych przypadkach użyto osobnej kategorii nazwanej "Polska". W cyklu rocznym najwięcej powodzi odnotowano latem (46%), a najmniej jesienią (8%). Do oceny intensywności powodzi użyto dwie klasyfikacje zaproponowane przez Brázdila i in. (2006) oraz Barriendosa i Coeura (2004). Wg pierwszej klasyfikacji aż 33% powodzi zakwalifikowano do kategorii „powódź ponadprzeciętna, czyli ponadregionalna”, natomiast wg kryteriów klasyfikacji drugiej zdecydowanie dominowały powodzie określone jako „nadzwyczajne” (70%). Główną przyczyną zidentyfikowanych powodzi w Polsce, wg podziału zaproponowanego w pracy Lambora (1954), był deszcz (44%). Do analizy istotności trendów występowania powodzi wykorzystano test Manna-Kendalla. Analiza wykazała, że częstość powodzi w Polsce znacząco spadła (wartość $p < 0,05$) w latach 1501–2000. Z kolei pozytywne tendencje zaobserwowano w podokresach 1501–1800 i 1801–2000, przy czym istotna statystycznie tendencja wystąpiła jedynie w ostatnim okresie.

Introduction

In light of current climate change, extreme climatic and hydrological events (i.e., droughts, floods) are increasing globally (Rohde, 2023). Floods are one of the most hazardous phenomena that inherently have dire consequences for society (Diodato et al., 2023). In recent decades, in Poland, floods have also played a disastrous role in human lives and the country's economy. For example, Poland experienced three catastrophic floods in 1997, 2001, and 2010 that caused significant economic losses of PLN 12.5 billion (USD 3.6 billion) PLN 3 billion (USD 0.7 billion), and PLN 12.5 billion (USD 3.7 billion), respectively (Biedroń & Bogdańska-Warmuz, 2012; Kundzewicz et al., 2023). Thus, to better understand flood events and improve the current knowledge regarding these events, analyses of long-term trends of their frequency, intensity, and changes in genesis should be carried out.

The investigation of long-term changes in flood events requires sufficient and comprehensive datasets. Measurements of water level in rivers in Poland started very late, at the end of the 18th century (e.g., the first water gauge in Warsaw was installed in 1799, see p. 144 in Magnuszewski & Gutry-Korycka, 2009). However, the first continuous water level recorder (recorded on a paper roller) in the world was invented by Henry Palmer in 1831 (Palmer, 1831). This device was installed on the Thames River in Sheerness (UK) in 1832. As a result, the available instrumental series of hydrological measurements are quite short. To obtain information about flood occurrences before the instrumental period, documentary evidence is the most often used source of information. Documentary evidence can play an important role in retrieving historical floods from previous centuries by providing detailed and reliable information about historical floods in terms of their intensity and frequency. Floods, being one of the most important natural hazards, have been mentioned in various documentary evidence such as official books, newspapers, diaries, chronicles, and technical reports (Brázdil et al., 2006; Glaser et al., 2010). Previous studies have confirmed the capability of this category of proxy data in the investigation of various climatic and hydrological events in the past (Glaser & Stangl, 2004; Przybylak et al., 2005; Brázdil et al., 2006; Cœur & Lang, 2008; Kiss, 2019; Przybylak et al., 2020; Przybylak et al., 2023). In Poland, documentary evidence has also been used for the evaluation of historical floods, but the number of available publications is limited (Majewski, 1993; Bielański, 1997; Cyberski et al., 2006). Although the existing studies have helped to understand historical floods in Poland, the available information is usually modest in terms of original sources, descriptions of events (including estimation of intensity, consequences for environment and economy, causes), area and period of time for which investigation were carried out, etc. Many publications provide only a list of flood events.

Significantly more information about flood occurrences is available for the last 220 years (Makowski, 1994; Fal & Dąbrowski, 2001b, 2001a; Kotarba, 2004; Magnuszewski & Gutry-Korycka, 2009; Zielonka et al., 2010; Magnuszewski et al., 2012; Kubiak-Wójcicka, 2014). Most publications about floods in Poland are published in Polish and therefore are not known by scientific communities globally (see, e.g., review papers written by Brázdil et al. (2006) and Tarasova et al. (2019) [section 3] giving syntheses of flood occurrences in the European countries in the last 1000 years based on papers published in the period 1985–2018). The more detailed reviews of the literature are presented in **P1** and **P3**.

The very limited knowledge about flood occurrences and their spatial-temporal changes in Poland in the pre-instrumental period (11th–18th centuries) was the main motivation to undertake the subject. A review of available literature reveals that a comprehensive study using high-quality documentary evidence is urgently needed to fill these gaps in knowledge. To reach this main aim of the work the following detailed objectives were formulated and undertaken:

1. Investigation of time changes in the frequency of floods in Poland
2. Assessment of time changes in the intensity of floods, including their extreme ones
3. Investigation of time changes in the genesis of floods
4. Comparison of some characteristics of floods (e.g., frequency, trends) in the historical period (1001–1800) and the instrumental period (1801–2000)
5. Comparison of some characteristics of floods (e.g., frequency, trends) in Poland with some other Central European countries

The output of this thesis will help to extend current knowledge about historical floods in Poland and contribute to improving historical hydrology and climatology research in Central Europe.

Materials and methods

Throughout history, there have been several changes to Poland's borders. In historical times, Poland's state borders were completely different from nowadays (see Fig. S1). Consequently, the country's current borders were examined to analyze flood events in Poland in the 11th–18th centuries. In addition, to obtain deeper knowledge about the spatial distribution of floods in Poland, the research was conducted for six major regions (Baltic Coast and Pomerania, Greater Poland, Masovia, Masuria-Podlasie, Lesser Poland, Silesia) and three main basins (Baltic Coast rivers, Oder River, and Vistula River) (see Fig. 1). For floods attributed to the Baltic Coast rivers basin, two regions of the Neman and Pregolya basins are also included because there are only a few weather notes about floods in these regions. Nevertheless, the basins of the two

longest rivers, namely the Oder and the Vistula, are the most significant basins for historical flood assessment. Therefore, the analysis and distinction of all floods are attributed to the mentioned six major regions and three river basins. In some cases, the category “Poland” was used to define areas of floods when there was no information about the place(s) of flood occurrences.



Fig. 1. Poland's main regions and river basins (Fig. 1. was created in ArcGIS 10.8.2 software. The 3D map of Poland was created using rayshader package in R-studio.)

To conduct this thesis, several comprehensive databases were created based on various sources from documentary evidence. These were one database of flood events in Poland each for the 11th–15th centuries, 16th century, and 17th–18th centuries and one updated and complete version for the 11th–18th centuries, as listed below:

- 11th–15th centuries <https://doi.org/10.18150/WD18XJ>
- 16th century <https://doi.org/10.18150/T3RXRI>
- 17th–18th centuries <https://doi.org/10.18150/VLPAPG>
- 11th–18th centuries <https://doi.org/10.18150/VLTVD9>

These databases contain detailed information, including: the year, month (or season), and day (if recorded) of the event; the original description of events; the source for described events; the quality of the source; and the classification of flood intensity and genesis. In the investigation of floods in Poland in the 11th–18th centuries, 563 sources and 1,345 weather notes

were used (Fig. 2). To compare flood frequency in Poland for the historical period (11th–18th centuries) and the contemporary era, information about floods in Poland in the 19th–20th centuries was gathered from the literature (Majewski, 1993; Bielański, 1997; Mudelsee et al., 2003; Grześ, 2008; Kasprzak, 2010; Blöschl et al., 2020).

A quality assessment was conducted for each source by historians through a critical analysis and divided into three categories; 1 – weak, 2 – moderate, and 3 – high to choose an appropriate source and weather note(s) for classification of floods. The sources are categorized as; 1 – weak, if the information is derived from secondary literature rather than the original source; 2 – moderate, if the information is written in centuries after the flood occurrence, and 3 – high, if the information is written in a source in the same period that the flood event occurred and provides precise information.

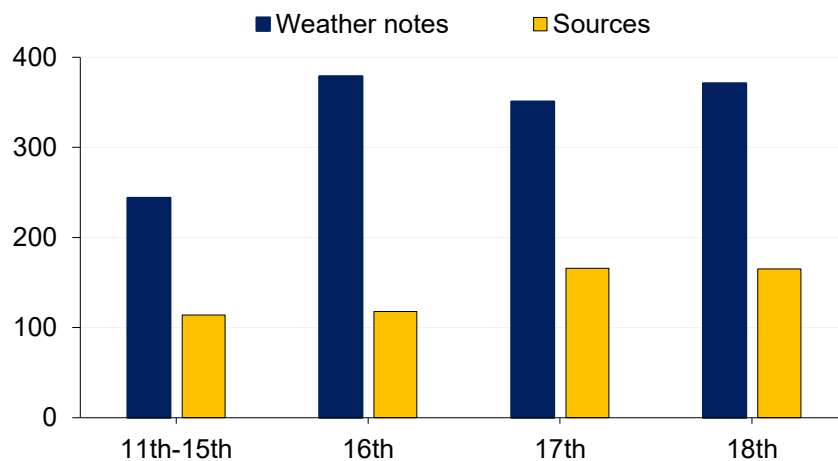


Fig. 2. Number of used sources and weather notes to assess floods in Poland in the period 1001–1800 (source: P4, updated)

To distinguish flood intensity and genesis, it is important to use a reliable indexation. Thus, for the classification of the intensity of floods in Poland, the two most widely used and reliable classifications (Barriendos & Coeur, 2004; Brázdil et al., 2006) for characteristics of historical floods in Europe were used. Also, to identify flood event origin, the Lambor (1954) source was used. Based on the Brázdil et al. (2006b) classification, the following categories of floods were distinguished: “floods” without detailed information, “smaller regional floods,” “above average floods,” and “floods with disastrous impact.” In the classification of the flood intensity introduced by Barriendos and Coeur (2004), floods are divided into “ordinary,” “extraordinary,” and “catastrophic.” Lambor (1954) proposed four classes for the leading cause of floods, namely “rain,” “snowmelt,” “winter-related floods,” and “storms.” The new category of “anthropogenic” was added to Lambor's (1954) classification to cover floods caused directly by human impact. The capability and reliability of these classification propositions in historical

flood indexation were approved in historical flood studies (Glaser et al., 2010; Retsö, 2015; Alcoforado et al., 2021; Ghazi et al., 2023a; Ghazi et al., 2023b; Ghazi et al., 2024). Tables S1 and S2 (Appendix 1) show detailed information about flood intensity and the classification of the origin of floods occurring in Poland in the period 1001–1800.

In the assessment of floods based on the mentioned databases, in several cases, more than one flood occurred in some years. In these cases, to distinguish floods, the information provided in weather note(s) is used. Thus, if the weather note(s) mentions the occurrence of floods in different rivers, it is considered a distinct event. Additionally, in cases where floods occur in the same river during the same year but in distinct months or seasons, they were identified as separate floods if the period between them was longer than seven days.

To summarize, to conduct this thesis, the following procedure was utilized:

1. Creation of a comprehensive database of flood events in Poland in the 11th–18th centuries based on documentary evidence
2. Assessment of various sources and their quality to use the best and most reliable sources for the classification of floods
3. Classification of flood intensity and genesis listed in the database separately by project members, who included climatologists, historians, and a hydrologist to overcome possible biases
4. Final agreement on classification of flood intensity and origins during meetings, if differences in individual classifications were noted
5. Approved database of floods was used for all research analyses presented in publications (P1–P4).

The summary of the methodology to conduct this research is depicted in Fig. 2 presented in **P1** and **P2**.

In this thesis, it is important to note that distinguishing floods from other high-flow or high-water occurrences in historical records due to potential biases in human testimonies can be a challenge. To overcome and/or minimize this obstacle in flood analysis, using proposed flood classification criteria, a weather note was considered to describe a “high-water” only if it met the category “0” (ordinary flood) in the Barriendos and Coeur (2004) classification (see Table S1).

To assess potential changes in the frequency of flood events, Mann–Kendall (MK) tests, as outlined by Mann (1945) and Kendall (1948) were used. The MK test is a non-parametric method widely used in hydrological and climatological studies to identify trends in time series. In the MK test, a p-value is calculated to express the probability that the test statistic is as

extreme as the observed one, assuming that the null hypothesis is true. In addition, alpha (significance level, e.g., 0.05) is used to establish the threshold for statistical significance. Generally, if ($p < \alpha$), it suggests a statistically significant trend within the dataset. On the other hand, if ($p \geq \alpha$), it implies the absence of significant trends within the dataset. To mitigate uncertainties arising from missing data, decadal trend analyses we conducted. Previous studies, including those by Mangini et al. (2018), Blöschl et al. (2019), and Venegas-Cordero et al. (2022), have demonstrated the detailed information and capability of the MK test in analyzing flood frequency trends.

Results

Results of the investigation of flood occurrences in Poland in 1001–1800 are presented in [Table 1](#) and [Fig. 3](#). Results showed that 1,252 floods were registered in Poland in the mentioned period. Also, based on the investigation of flood occurrences in the contemporary era from literature, it was revealed that Poland witnessed 428 floods in the 19th–20th centuries. In general, in the 11th–20th centuries, the study period for which most floods were recorded was the 18th century (356). The numbers of floods in the other periods were 210 (11th–15th centuries), 345 (16th century), 341 (17th century), 187 (19th century), and 241 (20th century).

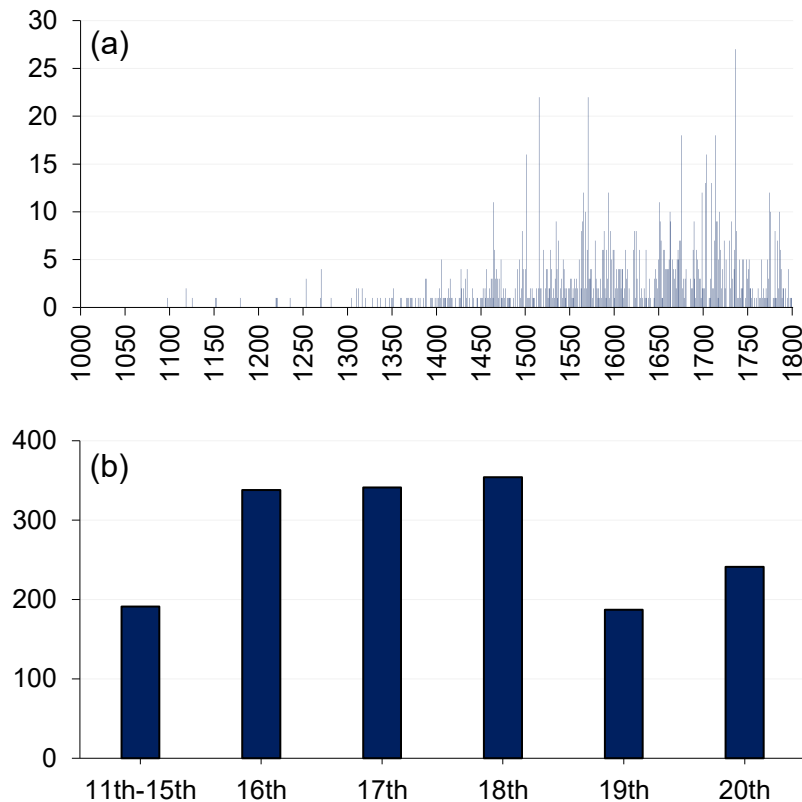


Fig. 3. Number of floods in Poland (a) annual frequency for the 11th–18th centuries and (b) flood occurrences in different centuries in Poland (11th–20th centuries) (source: **P4**, updated)

Table 1. Flood occurrences by year in Poland in the 11th–18th centuries

Time period	Year of flood occurrences in Poland in the 11 th –18 th centuries*
11th–15th centuries	1097, 1118, 1125, 1151, 1152, 1179, 1219, 1220, 1221, 1235, 1253 (3), 1269, 1270 (4), 1281, 1304, 1310 (2), 1312 (2), 1316 (2), 1320, 1328, 1333, 1337, 1342, 1347, 1349, 1350, 1351 (2), 1359, 1360, 1366, 1367, 1368, 1370, 1371, 1372, 1376, 1379, 1381, 1385, 1387 (3), 1388 (3), 1393, 1394, 1395, 1398, 1400, 1402, 1403 (2), 1404, 1405 (5), 1407, 1408, 1409, 1410, 1412, 1413 (2), 1414, 1415 (3), 1416, 1417, 1421, 1425, 1426, 1427 (4), 1428 (2), 1430 (2), 1432 (3), 1433, 1434 (4), 1437, 1440 (2), 1441, 1445, 1446, 1449, 1450, 1451, 1452 (2), 1454 (2), 1455, 1456 (4), 1457, 1458, 1459 (2), 1460, 1461 (3), 1462 (3), 1463, 1464 (11), 1465 (6), 1466 (3), 1467 (4), 1468 (3), 1469, 1470 (3), 1472 (5), 1473, 1474, 1475 (2), 1476, 1477 (2), 1479, 1480, 1481, 1482, 1483, 1486, 1488 (2), 1491 (4), 1493 (5), 1494, 1495 (2), 1496 (8), 1497 (4), 1500 (4)
16th century	1501 (16), 1502, 1503, 1504, 1505 (2), 1507 (2), 1508, 1509, 1510, 1512 (2), 1514 (2), 1515 (22), 1516 (2), 1517 (2), 1520 (6), 1522 (2), 1523 (4), 1524 (4), 1525, 1526 (2), 1527 (2), 1528 (6), 1529 (4), 1530, 1531 (2), 1532, 1533 (3), 1534 (9), 1535 (4), 1536, 1537 (7), 1539 (2), 1540 (3), 1541, 1542 (5), 1543 (4), 1544 (2), 1545, 1546 (2), 1548 (2), 1549 (2), 1550 (3), 1551 (3), 1552, 1553 (2), 1554, 1555 (3), 1556 (2), 1557 (3), 1558 (2), 1560 (5), 1562 (2), 1563 (8), 1564 (9), 1565 (12), 1566 (2), 1567 (10), 1568 (2), 1569 (6), 1570 (22), 1571 (3), 1572 (3), 1573 (4), 1574 (4), 1575, 1576 (2), 1578 (7), 1579 (3), 1580 (2), 1581, 1582 (2), 1583, 1584 (3), 1585, 1586 (6), 1587 (6), 1588 (8), 1589 (2), 1590, 1591 (6), 1592 (3), 1593 (12), 1594, 1595 (8), 1596 (5), 1598 (6), 1599 (6), 1600
17th century	1601 (2), 1602 (4), 1603 (2), 1604 (4), 1605 (4), 1606 (4), 1607 (2), 1608 (4), 1609 (4), 1610, 1611 (2), 1612 (6), 1613 (3), 1614 (4), 1616 (2), 1621 (6), 1622 (8), 1623, 1624 (8), 1625 (3), 1628 (6), 1629, 1630 (2), 1631, 1633 (2), 1634, 1635 (6), 1636, 1638, 1639 (3), 1640, 1644, 1645 (3), 1646 (4), 1647 (3), 1648 (2), 1649 (5), 1650 (11), 1651 (9), 1652 (7), 1653, 1654, 1655 (6), 1656 (6), 1657 (4), 1658 (4), 1659 (4), 1660 (4), 1661 (5), 1662 (10), 1663 (9), 1665 (5), 1666 (4), 1667 (3), 1668 (4), 1669 (2), 1670 (5), 1671 (6), 1672 (5), 1673 (7), 1674 (7), 1675 (18), 1676 (2), 1677 (3), 1678, 1679 (3), 1680 (4), 1685 (3), 1686 (2), 1687 (2), 1688 (6), 1689 (9), 1690 (3), 1691, 1692 (6), 1693 (5), 1694 (4), 1695 (3), 1696 (3), 1697, 1698 (12), 1699 (2), 1700 (2)
18th century	1701 (2), 1702 (13), 1703 (16), 1706, 1707, 1708 (3), 1709 (13), 1710 (2), 1711 (2), 1712 (7), 1713 (18), 1714 (9), 1715 (9), 1716, 1717 (5), 1718 (10), 1719 (6), 1720 (2), 1721 (4), 1723 (7), 1724 (2), 1725 (5), 1729 (7), 1730 (2), 1731 (9), 1732 (3), 1734 (4), 1735 (6), 1736 (27), 1737 (8), 1738, 1739, 1740 (5), 1741, 1742 (2), 1743 (2), 1744 (5), 1745 (5), 1747, 1748 (5), 1749 (3), 1750 (4), 1751 (5), 1752 (2), 1753 (2), 1754, 1755 (2), 1757, 1759, 1761 (2), 1763, 1764, 1765 (5), 1766, 1767 (2), 1768, 1769, 1770 (2), 1771, 1772 (5), 1773 (3), 1774 (12), 1775 (10), 1778, 1779, 1780 (8), 1781, 1782, 1783 (7), 1784 (2), 1785 (10), 1786 (6), 1787 (4), 1788, 1789 (2), 1790 (2), 1792 (2), 1794, 1795 (4), 1797, 1798, 1799

*Key: () – number of floods in parentheses if more than “1” in the mentioned year

By investigating flood occurrences in the river basin (Figs. 4 and 5), it was demonstrated that, in the 11th–18th centuries in the Oder River basin, a large number of floods (671) occurred, with the highest number of them (245) in the 16th century. Also, in the Vistula River basin, 522 floods were registered, with the greatest number (187) in the 18th century. The number of floods in the Baltic Coast rivers basin was only 31.

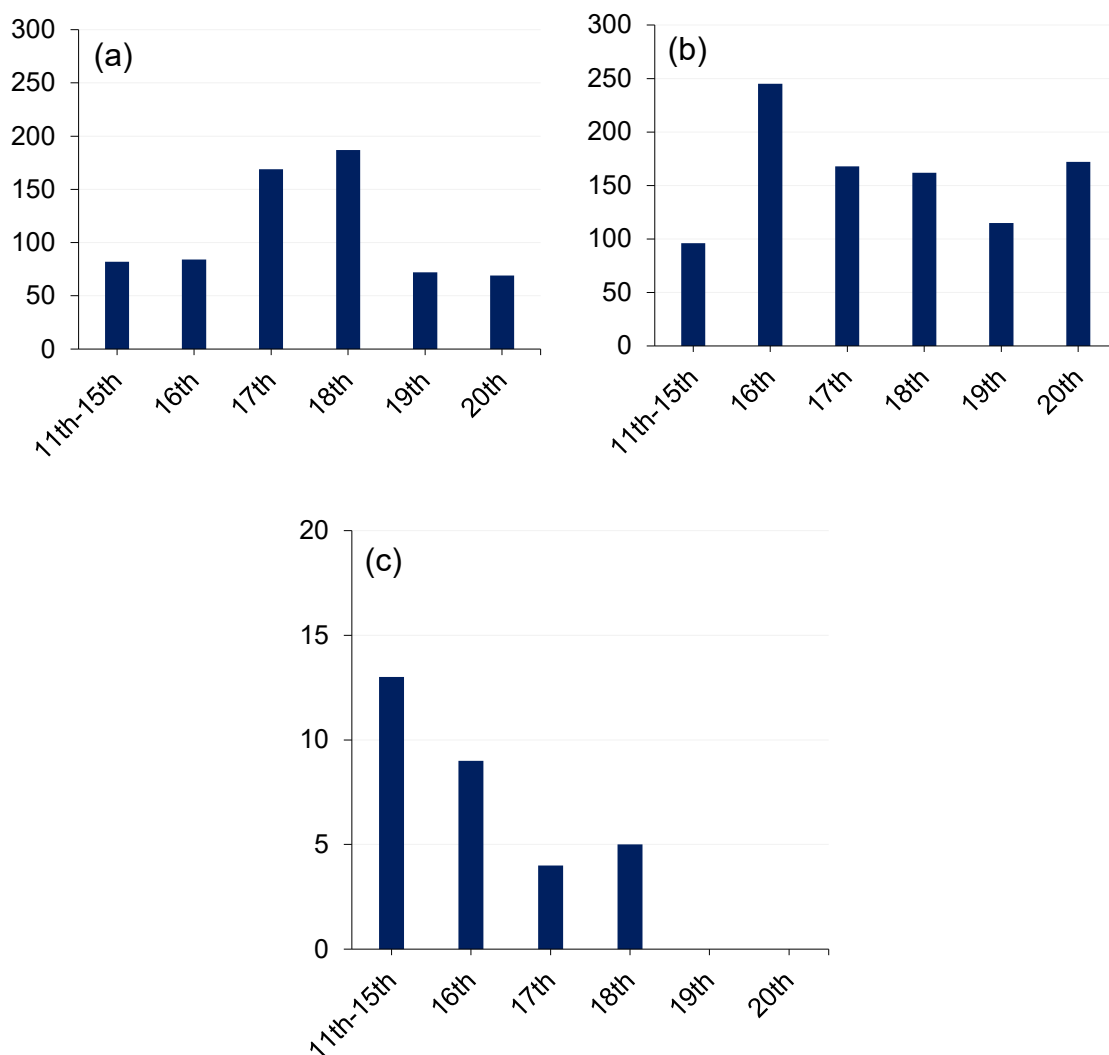


Fig. 4. Number of floods in Poland in the 11th–20th centuries in (a) the Vistula River basin, (b) the Oder River basin, and (c) the Baltic Coast rivers basin (there is no data for floods in the 19th and 20th centuries for this area)

(source: **P4**, updated)

Please note the scale difference in Fig. (c).

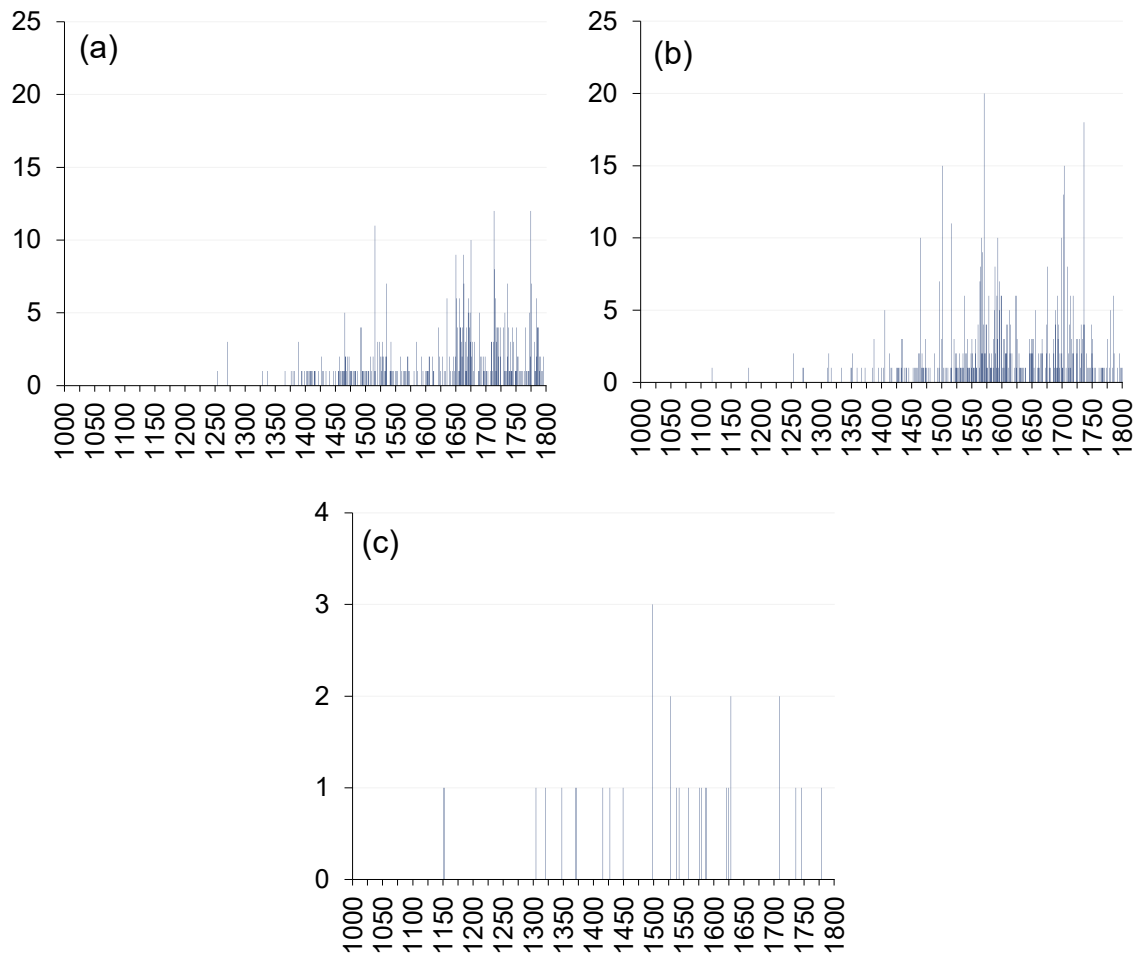


Fig. 5. Annual number of floods in Poland, AD 1001–1800: (a) Vistula River basin, (b) Oder River basin, and (c) Baltic Coast rivers basin (source: **P4**, updated)

Please note the scale difference in Fig. (c).

Identifying flood-rich periods for the study area and two river basins of Vistula and Oder was only possible from 1451 to 1800 (Table 2, Fig. 6) when the availability of documentary evidence and identified floods were more or less at the same level (see Fig. 3). To distinguish flood-rich periods in series of 11-year moving-average flood frequencies, a threshold (T) was calculated based on the equation:

$T = M + SD$, where:

M – mean annual value of flood frequency from the period 1451–1800

SD – standard deviation calculated based on series of 11-year moving averages, 1451–1800

Table 2. Flood-rich periods in Poland, 1451–1800

Region	Flood-rich period			
All Poland	1557–1579	1585–1596	1646–1681	1692–1746
Vistula River	1646–1683	1704–1725	1764–1792	–
Oder River	1556–1605	1689–1719	1726–1744	–

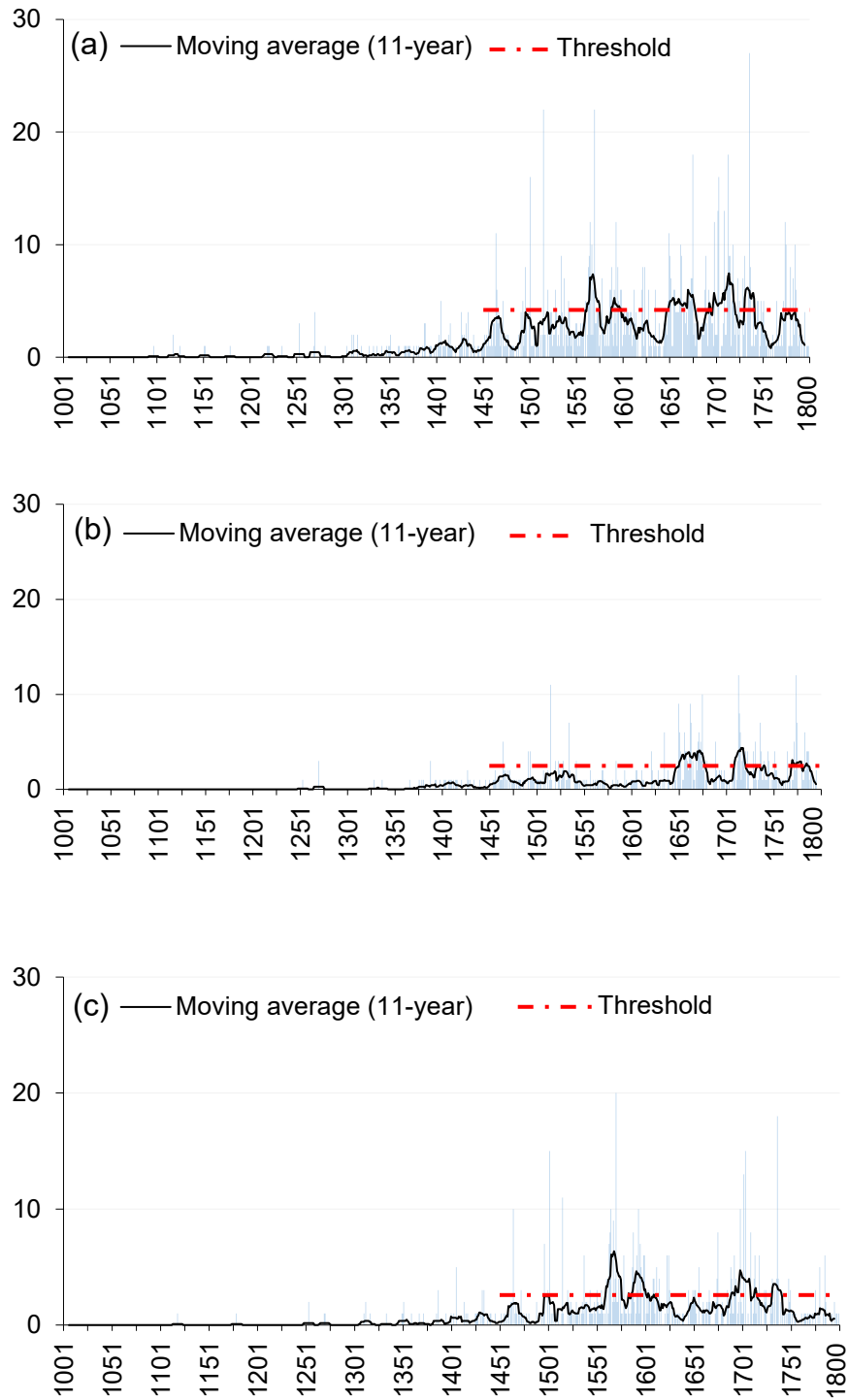


Fig. 6. Annual (bars) and 11-year mean (black line) frequencies of floods in the period 1001–1800 in (a) all of Poland, (b) the Vistula River basin, and (c) the Oder River basin with an indication of flood-rich periods (years above red lines)

By investigation of spatial variations of floods in Poland in 1001–1800 (Fig. 7), it was revealed that the Silesia region experienced the greatest number of floods (533, 43%). The number of floods in other regions was, in descending order: Baltic Coast and Pomerania (289, 23%) Lesser

Poland (212, 17%) Greater Poland (109, 9%) Masovia (53, 4%), and Masuria-Podlasie (11, 1%). Only 46 floods (4%) belong to the category “Poland.”

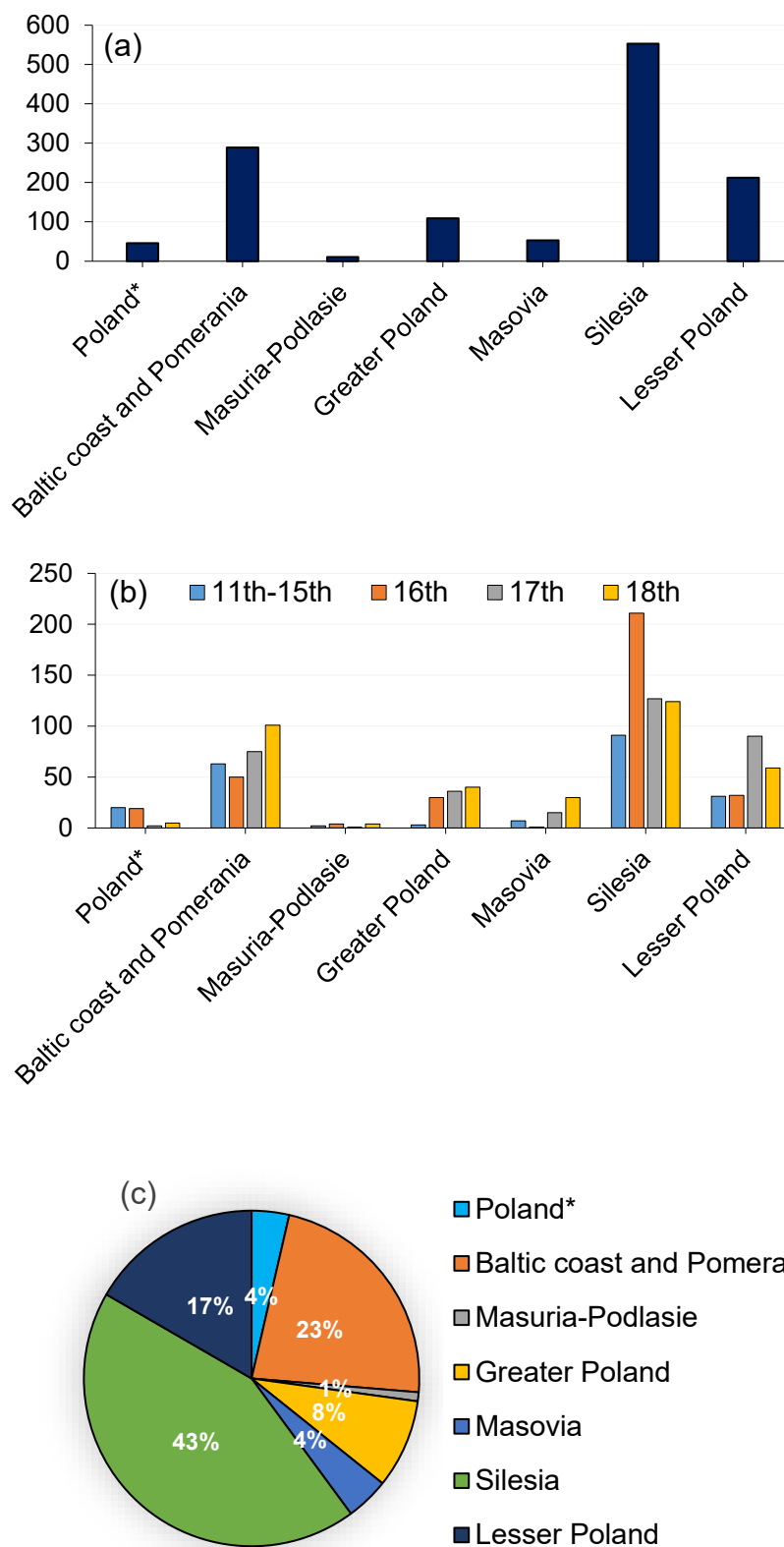


Fig. 7. Number of floods in Poland in 1001–1800; (a) floods in different regions, (b) floods in different sub-periods and regions (c) floods by percent for different regions (source: **P4**, updated)

*Category of “Poland” with no details about the region

Estimation of floods based on the season/month of the occurrences (Figs. 8–10) showed that the season in which most floods occurred was summer (385, 46%), Also, floods were more common in spring (227, 28%) than in autumn (67, 8%) or winter (150, 18%). In a detailed investigation of monthly flood frequency, it was indicated that abundant numbers of floods (>100) occurred in the months of July (159), August (117), June (109), and March (103), while the lowest numbers were recorded in October (16) and November (12).

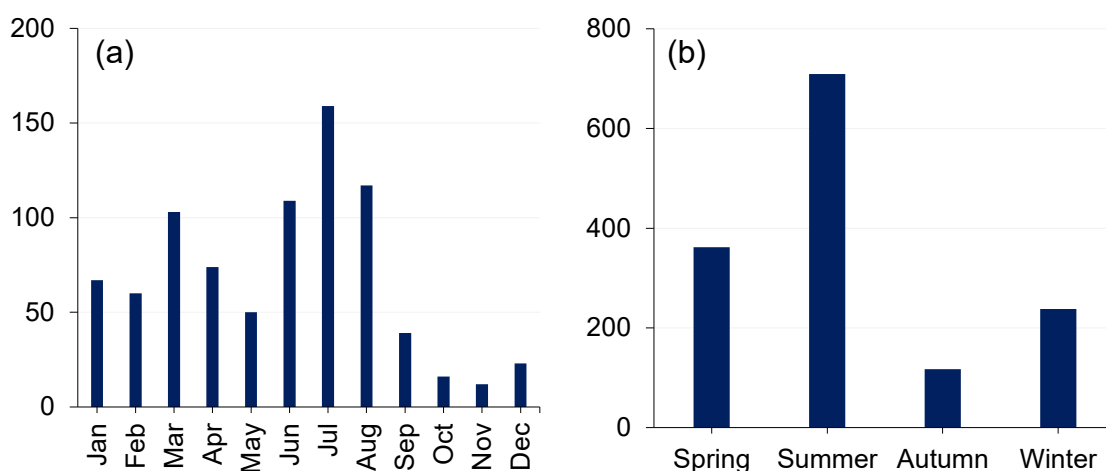


Fig. 8. Number of floods in Poland in the 11th–18th centuries (a) monthly and (b) seasonal (source: **P4**, updated)

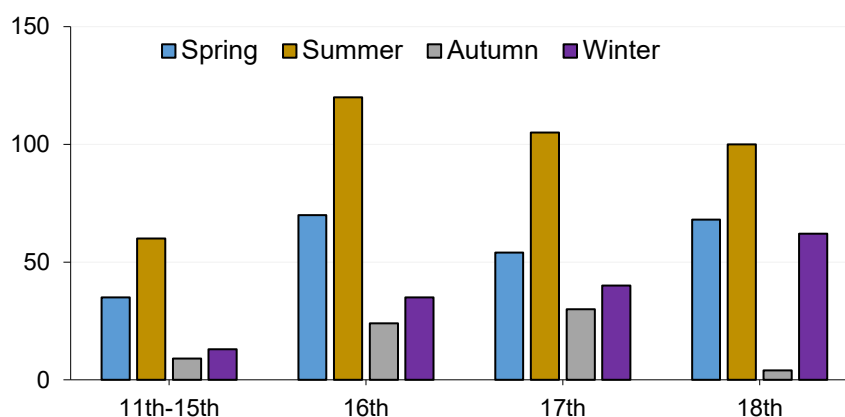


Fig. 9. Number of floods in Poland in the different centuries based on the season (source: **P4**, updated)

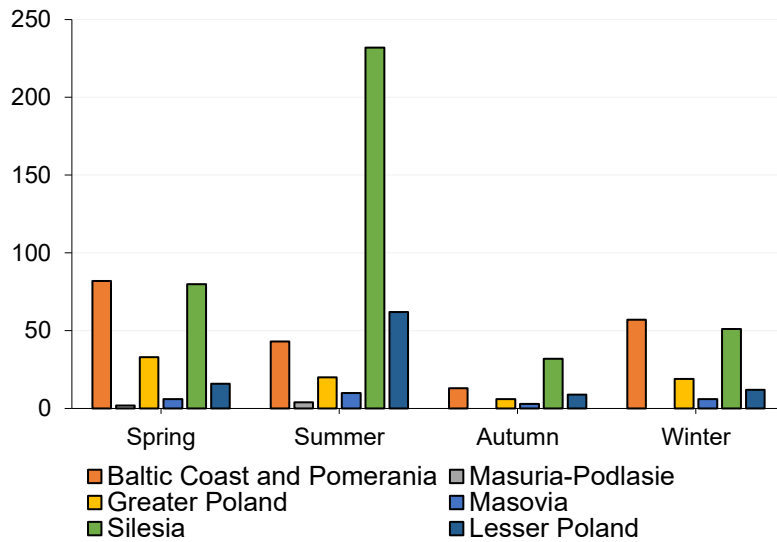


Fig. 10. Seasonal frequency of floods in the main six regions of Poland, 1001–1800 (source: **P4**, updated)

The classification of intensity and genesis of floods was carried out based on Brázdil et al. (2006), Barriendos and Coeur (2004) and Lambor (1954) classifications (Fig. 11). The categories of the Brázdil et al. (2006) classification to which the most floods were classified were “above-average, or supra-regional flood” and “smaller, regional flood”, at 408 (33%) and 403 (32%), respectively. Under the Barriendos and Coeur (2004) classification, the category “extraordinary” (862, 70%) was more common than other categories. Classification of flood genesis demonstrated that the largest single cause of floods in Poland in the study period was rain (533, 44%). The contribution of other factors to flood occurrences was lower, including snowmelt (62, 5%), storm (23, ~2%), winter (77, 6%), and anthropogenic (7, ~1%). For 42% of floods, it was not possible to identify the origin of floods based on the weather notes.

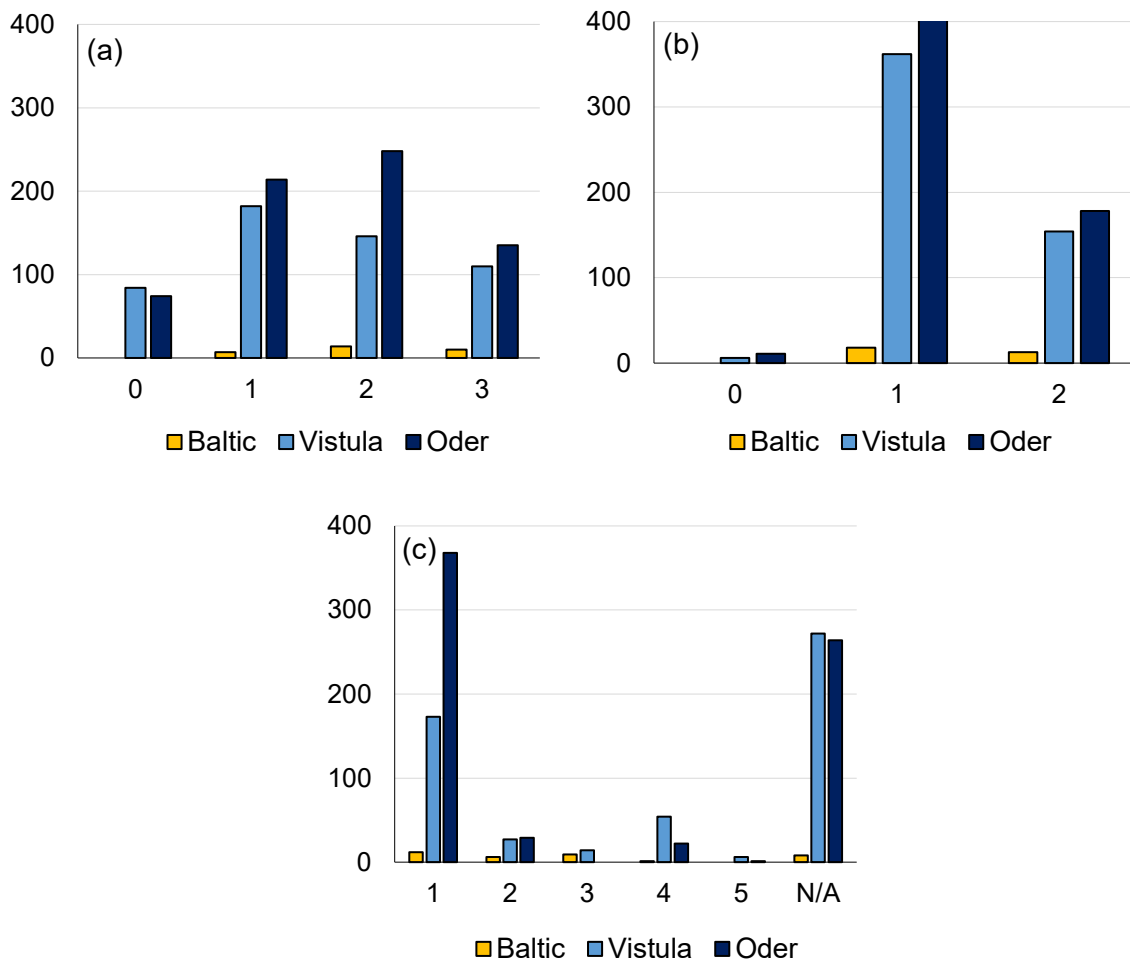


Fig. 11. Number of floods in the river basins of Poland in the 11th–18th centuries based on (a) Brázdil et al. (2006), (b), Barriendos & Coeur (2004) and (c) Lambor (1954) classifications (source: **P4**, updated)

Estimation of flood intensity in the main six regions of Poland in the 11th–18th is depicted in Fig. 12. According to the Brázdil et al. (2006) classification (Fig. 12a), the largest category of floods was “above-average, or supra-regional flood”, with the greatest number in Silesia (212) and the lowest in Masuria-Podlasie (4) region. In the Barriendos and Coeur (2004) classification (Fig. 12b), for both categories of “extraordinary” and “catastrophic,” the highest numbers occurred in the Silesia and Baltic Coast and Pomerania regions.

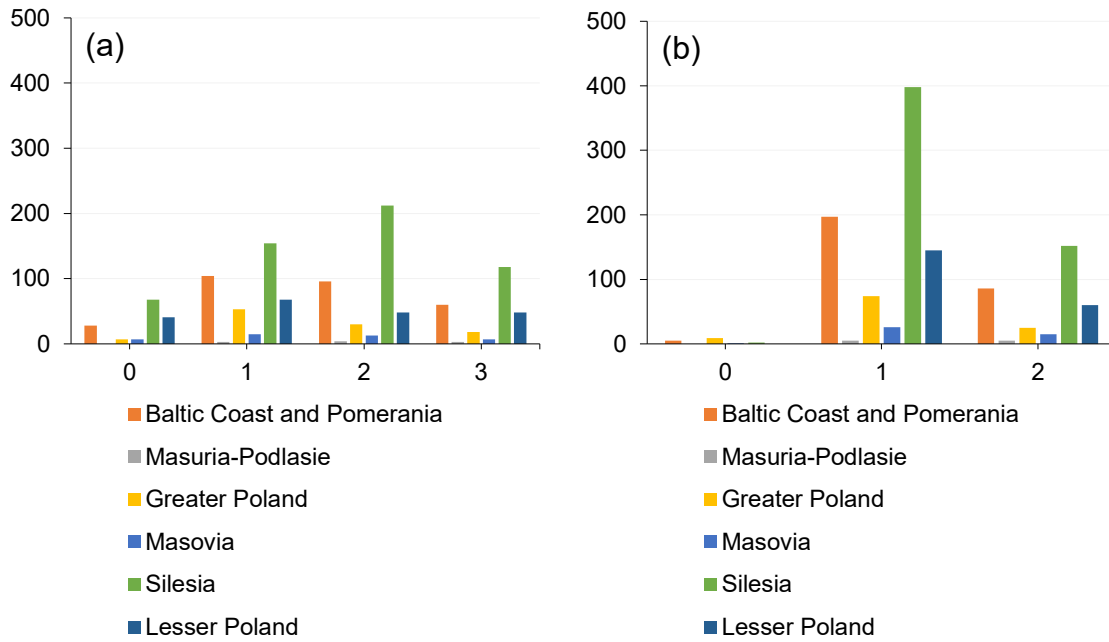


Fig. 12. Classification of flood intensity based on (a) Brázdil et al. (2006), and (b), Barriendos & Coeur (2004) for the main six regions of Poland (source: **P4**, updated)

Through a detailed analysis of floods based on genesis in different sub-periods (Fig. 13), there is clear evidence of rain and its subtypes to the contribution of floods in Poland in the 11th–18th centuries. The highest contribution of rain to flood occurrences was in the 16th century and the lowest was in the 18th century. The contribution of “snowmelt” and “winter” was relatively higher in the 18th century than in other sub-periods, while in the 11th–15th centuries, occurrences of floods by “storm” had a greater share than in other periods.

In the different sub-categories of the origin of floods for different periods (Fig. 13b), it is revealed that for floods caused by rain, the category of rain without information of rain type “1 (N/A)” was higher than either torrential (1a) or frontal (1b) or long-lasting (1c).

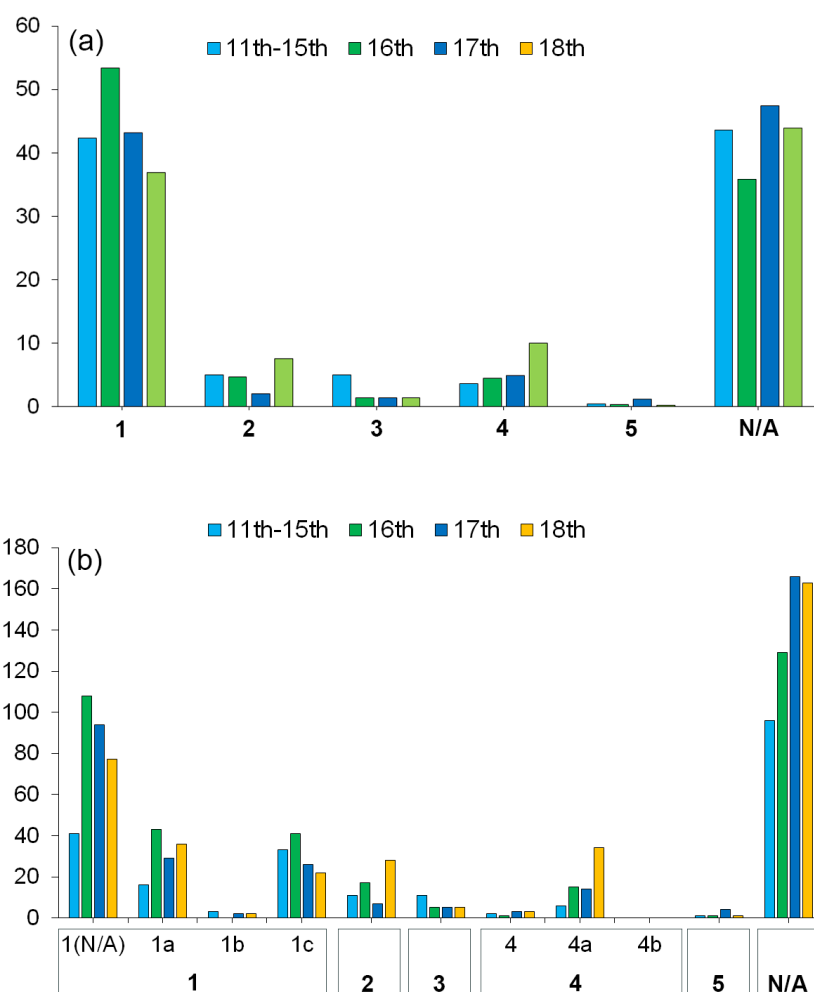


Fig. 13. Frequency of type of origin of floods in Poland in the period 11th–18th centuries (a) relative frequency based on Lambor's (1954) classification (b) number of floods

*Key: rain (N/A) – there is no information about the type of rain

As mentioned in the previous section, rain and its different subtypes constituted the single largest cause of floods in the study area. Thus, changes in seasonal occurrences of floods caused by rain category were assessed in detail (Fig. 14).

Although rain was the single largest main cause of floods in the study area, its subtype was not clearly distinguishable for all floods based on the available weather notes. According to the analysis, “rain (N/A)” is the predominant category in all seasons (48% in spring, 58% in summer, 63% in autumn, and 44% in winter). Of the other sub-types of rain categories (torrential rain [1a], frontal rain [1b], and long-lasting rain [1c]), floods were most frequently caused by torrential rains in spring (28%) and summer (20%) and by long-lasting rains in autumn (23%) and winter (24%).

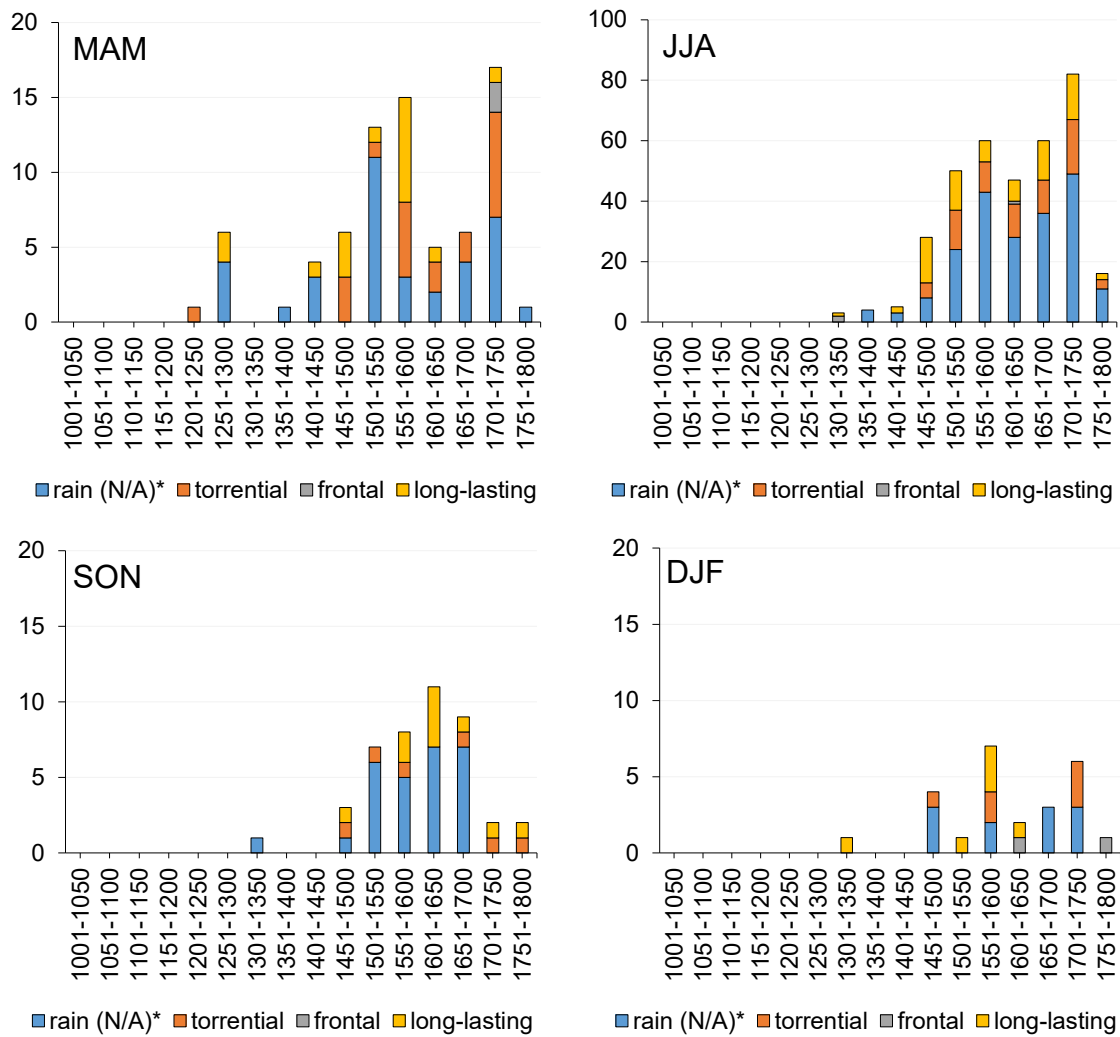


Fig. 14. Seasonal (MAM, JJA, SON, DJF) flood frequencies in Poland in the period 1001–1800 caused by rain and its subtypes (source: **P4**, updated), please note the scale difference for summer (JJA)

The analysis of extreme floods was carried out based on the category “3 – above average, or supra-regional flood on a disastrous scale” in the Brázdil et al. (2006) classification and category “2 – catastrophic” in the Barriendos and Coeur (2004) classification. Extreme floods are presented in Table 3. Moreover, the frequency of extreme floods and time changes in the share (%) of extreme floods relative to all floods are depicted in Fig. 15. On average, assessment of the frequency of extreme floods (Fig. 15a) showed that the greatest number of extreme floods was distinguished in the 16th century (85) and in the 17th century (91) based on the classifications of Brázdil et al. (2006) and Barriendos and Coeur (2004), respectively. On the other hand, the lowest number of them was in the 11th–15th centuries (48) according to Brázdil et al. (2006) and in the 18th (80) according to Barriendos and Coeur (2004) (Fig. 15a).

Estimation of the relative frequency of extreme floods to all floods (Fig. 15b) demonstrated that, for the Brázdil et al. (2006) classification, it was for the sub-period of the

16th century that the relative frequency of extreme floods was highest (by 25%), while according to Barriendos and Coeur (2004), the sub-period of the 11th–15th centuries exceeded the other sub-periods by 41%.

Table 3. Year and number (in parentheses) of extreme flood occurrences in Poland in the 1001–1800 according to “category 3” in Brázdil et al., 2006, and “category 2” in Barriendos & Coeur, 2004) classification

Time period	Brázdil et al. (2006)	Barriendos & Coeur (2004)
11 th –15 th centuries	1253, 1270 (4), 1304, 1310 (2), 1316 (2), 1320, 1370, 1372, 1393, 1402, 1410, 1432 (3), 1433, 1434, 1445, 1449, 1460, 1462 (3), 1464 (11), 1465, 1466 (2), 1466, 1467 (2), 1470, 1497 (3), 1500	1221, 1253 (3), 1270 (4), 1304, 1310 (2), 1316 (2), 1320, 1337, 1351, 1370, 1372, 1376, 1385, 1387 (2), 1388 (2), 1393, 1402, 1403, 1405 (3), 1410, 1415, 1426, 1427 (2), 1428, 1432 (3), 1433, 1434, 1445, 1449, 1450, 1456, 1460, 1462 (2), 1464 (11), 1465, 1466 (2), 1467 (2), 1468, 1470 (2), 1475 (2), 1476, 1477, 1488 (2), 1488, 1491, 1493 (3), 1496 (4), 1497 (3), 1500 (2)
16 th century	1501 (9), 1512, 1515 (6), 1522, 1524 (2), 1526, 1527 (2), 1528 (3), 1533 (2), 1534 (5), 1535, 1536, 1537 (3), 1540, 1549, 1550, 1551 (2), 1555, 1556, 1563 (2), 1564 (7), 1565 (2), 1567 (5), 1569 (2), 1570 (5), 1572 (3), 1578 (4), 1582, 1584, 1585, 1586 (2), 1593, 1595, 1596, 1598 (3)	1501 (9), 1508, 1512 (2), 1515 (6), 1522, 1524 (2), 1526, 1527 (2), 1528 (3), 1533 (2), 1534 (5), 1534, 1535, 1536, 1537 (3), 1540, 1549, 1550, 1551 (2), 1555, 1556, 1563 (2), 1564 (7), 1565 (2), 1567 (5), 1569 (2), 1570 (6), 1572 (3), 1578 (4), 1582, 1584, 1585, 1586 (2), 1593, 1595, 1596 (3), 1598 (3)
17 th century	1605, 1606 (2), 1607, 1608 (2), 1609, 1613, 1622 (4), 1624, 1633, 1636, 1639, 1646, 1649, 1650 (7), 1651 (2), 1652 (3), 1657 (2), 1659, 1661 (2), 1662 (3), 1663 (2), 1666 (2), 1667, 1669, 1670, 1671 (2), 1672, 1674 (2), 1675, 1676 (2), 1687, 1688, 1689 (2), 1692, 1694, 1698	1603 (2), 1604 (2), 1605, 1606 (2), 1607, 1608 (2), 1609 (2), 1611, 1612, 1613, 1621 (2), 1622 (4), 1624 (2), 1628 (2), 1633, 1635, 1636, 1639 (2), 1646 (2), 1647 (2), 1649 (3), 1650 (7), 1651 (4), 1652 (3), 1657 (2), 1659, 1661 (3), 1662 (5), 1663 (2), 1665, 1666 (2), 1667, 1669, 1670, 1671 (2), 1672, 1674 (3), 1675 (3), 1676 (2), 1687, 1688, 1689 (3), 1693, 1694 (2), 1698, 1700
18 th century	1702 (5), 1707, 1708, 1709 (2), 1717, 1719 (2), 1723, 1725 (2), 1729, 1731 (2), 1735, 1736 (15), 1737 (3), 1741, 1745, 1747, 1749, 1750, 1759, 1763, 1765, 1772 (2), 1773, 1774 (6), 1775, 1779, 1780, 1783, 1784, 1785 (3), 1786, 1795	1702 (5), 1703, 1707, 1708, 1709 (5), 1713, 1717, 1719 (2), 1723, 1725 (2), 1729 (2), 1731 (3), 1735 (2), 1736 (16), 1737 (3), 1741, 1745, 1747, 1749, 1750, 1751, 1755, 1759, 1763, 1765, 1772 (2), 1773, 1774 (6), 1779, 1780 (2), 1783 (3), 1784, 1785 (5), 1786 (2), 1795

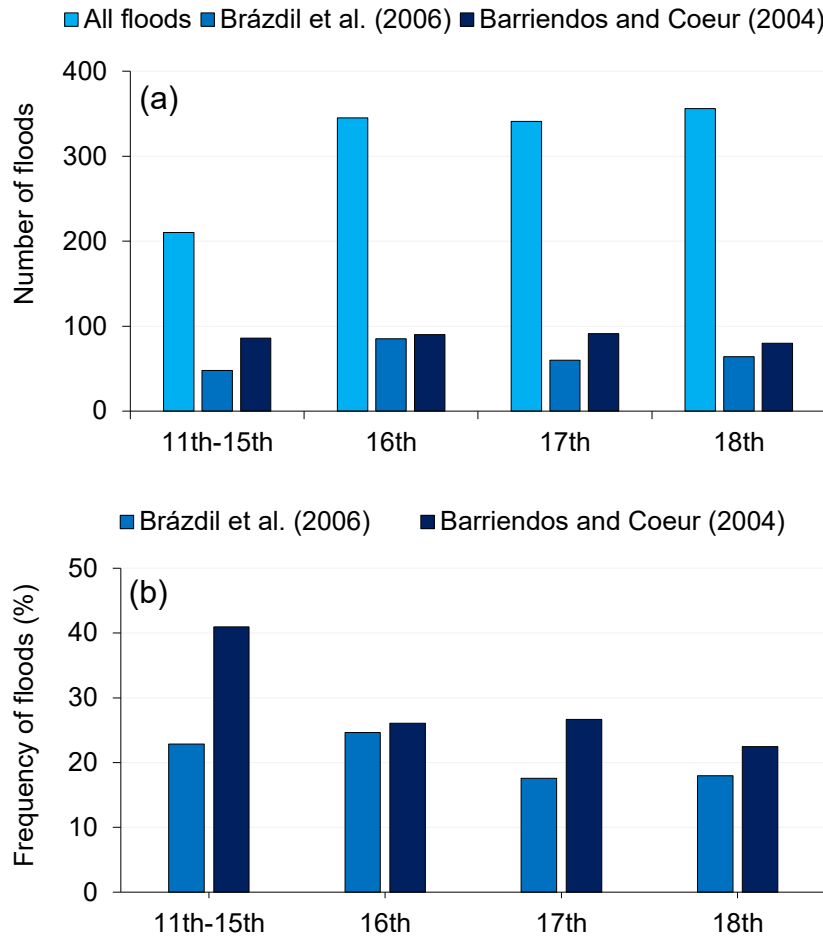


Fig. 15. (a) Number of all floods and extreme floods (“category 3” in Brázdil et al., 2006, and “category 2” in Barriendos & Coeur, 2004) for Poland in the study sub-periods, (b) Percentage share of extreme floods relative to all floods

Flood occurrences in Poland for different places (major cities) (Fig. 16) indicated that floods were more frequent (≥ 20) in some places in Poland than others. In general, floods occurred most frequently in the following cities/towns: Wrocław (72), Bolesławiec (59), Gdańsk (52), Kraków (50), Poznań (50), Nysa (34), Toruń (31), Malbork (30), Żytawa (29), Krosno Odrzańskie (25), Mirsk (25), Gubin (24), Warsaw (23), Zgorzelec (23), Kłodzko (22), Gorzów and Wielkopolski (20). Floods were more common in the southwest and southeast of Poland than in other parts of the country.

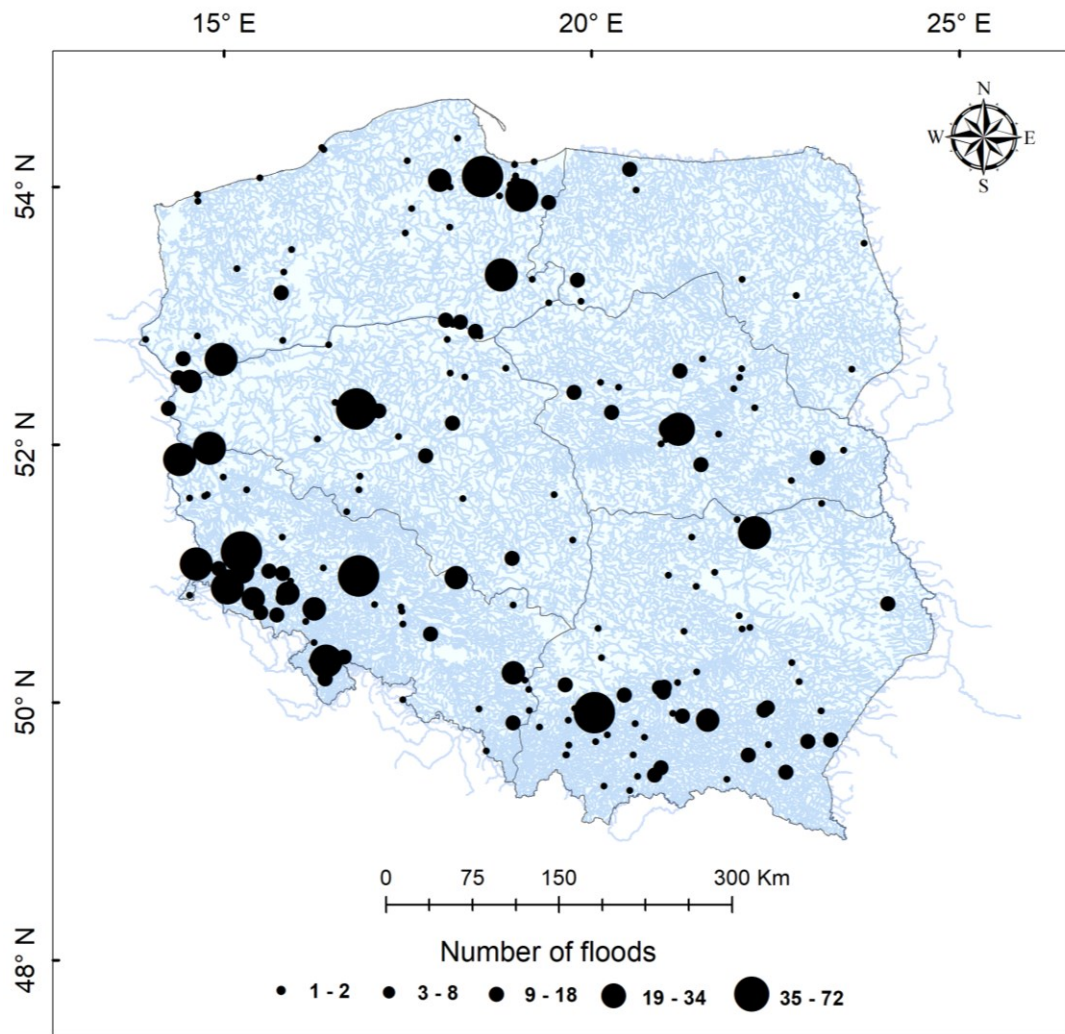


Fig. 16. Spatial distribution and frequency of floods in Poland in the 11th–18th centuries (source: P4, updated)

Changing flood frequencies over time in the era of global warming as a research topic has great importance for scientific communities. Thus, based on the comprehensive and detailed database of floods in Poland, variations in the flood frequency and their trends were assessed (Fig. 17). It is important to be aware that, due to the many gaps in ten-year frequencies of floods, the period of the 11th–13th centuries was excluded from this assessment. Thus, flood frequencies are presented from 1301 to 2000, and their trends were evaluated for three sub-periods: 1501–1800, 1501–2000, and 1801–2000. In addition, flood frequencies for a three-decadal moving average are presented for the entire period (1301–2000).

Results of the MK test trend analysis for the frequency of decadal trends in Poland demonstrated that from 1501 to 1800 there is no statistically significant trend ($p\text{-value} > 0.05$), while there is an increasing and decreasing statistically significant trend ($p\text{-value} < 0.05$) for the periods of 1801–2000 and 1501–2000, respectively.

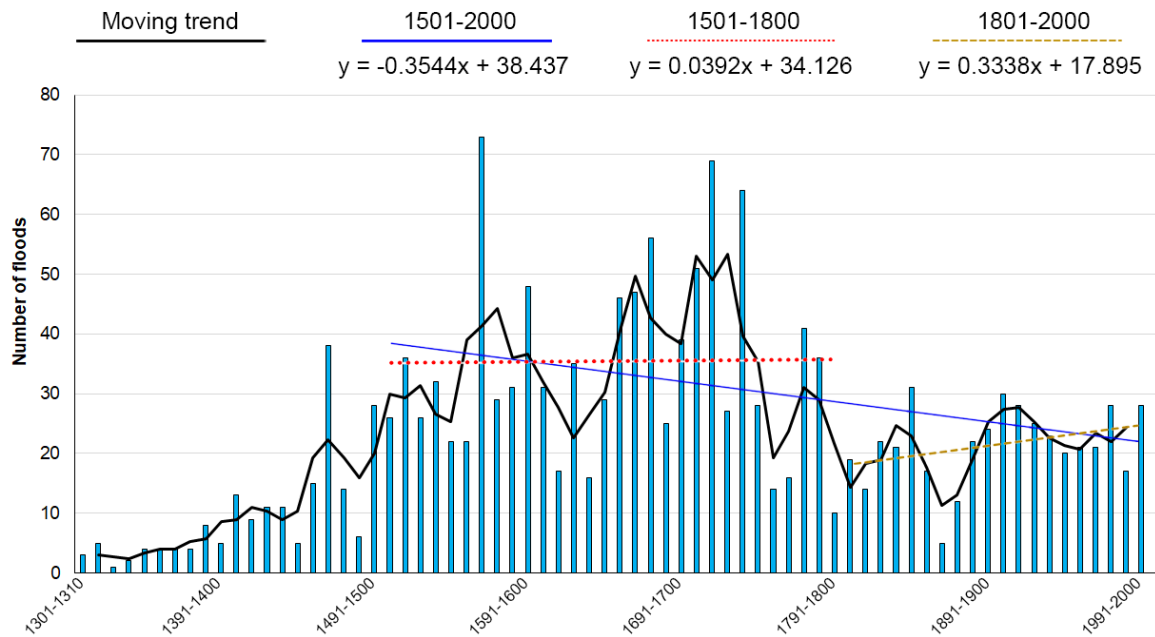


Fig. 17. Change in decadal (bars) and moving 3-decadal means (black line) flood frequencies in Poland from AD 1301–2000 and their long-term trends (color lines) (source: **P4**, updated)

Even though there is no significant trend for flood frequencies from 1501 to 1800, flood frequency clearly decreased starting around the middle of the 18th century and continued until the turn of the 20th century. In contrast, a significant increase in the number of floods can be seen in the 20th century, and it is projected to continue until the end of the 21st century (Alfieri et al., 2015; Tabari, 2020a).

Due to global warming, it is projected that the frequency of extreme floods will increase in the future. Therefore, the variations and trends of extreme floods were investigated based on the definition in Brázdil et al. (2006) (“category 3”), and in Barriendos and Coeur (2004) (“category 2”). Changes in annual extreme flood frequencies in Poland in the period of 1001–1800 and their trends for the period of 1501–1800 are presented in Fig. 18.

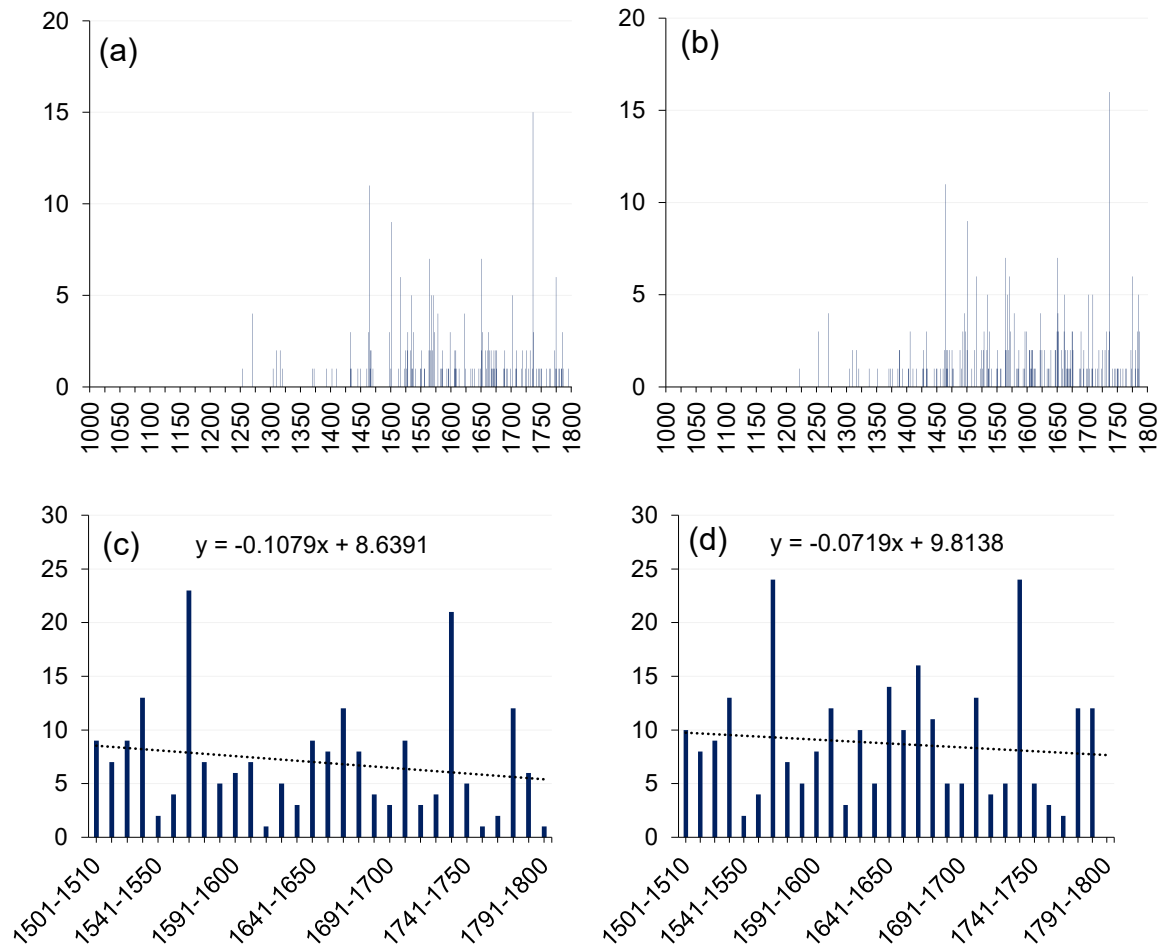


Fig. 18. Annual (a, b) and decadal (c, d) frequency of extreme floods in Poland in the 11th–18th centuries (source: **P4**, updated)

Key: (a) and (c) – “category 3” in Brázdil et al. (2006) classification, (b) and (d) – “category 2” in Barriendos & Coeur (2004) classification

The results depicted in Fig. 18 demonstrate that there are decreasing, statistically significant (p -value < 0.05) trends for the decadal frequency of floods in 1501–1800. In addition, the highest frequency of floods was observed in the periods 1501–1540 and 1651–1690.

Discussion

The uncertainty and biases in documentary evidence pose great challenges when reconstructing extreme phenomena like historical floods (Brázdil et al., 2005b). By using the most reliable sources and detailed weather notes, this thesis has tried to overcome these challenges and biases. To provide readers with a clear insight into historical floods in Poland, the results provided here were compared with some of the studies on the history of floods in this region. For floods that occurred in the Vistula River basins, the information was gathered from two sources Majewski (1993) and Bielański (1997). The history of floods in the Oder River basin was collected from Mudelsee et al. (2003) and Kasprzak (2010). There is also the list of floods in Poland in the

sources provided by Grześ (2008) and Blöschl et al. (2020). As already mentioned in the results section here, 1,252 floods were identified for the area of Poland in the 11th–18th centuries. The number of floods in this research for all sub-periods for the Vistula River (522) and the Oder River (671) is significantly greater than all previous studies (Table 4).

Table 4. Number of floods in Poland in the 11th–18th centuries according to various sources (source: P4, updated)

Period	Current study		Blöschl et al. (2020)	Kasprzak (2010)	Grześ (2008)	Mudelsee et al. (2003)	Bielański (1997)	Majewski (1993)
	Oder River basin	Vistula basin	Vistula and Oder basins	Oder River basin	Vistula and Oder basins	Oder River basin	Upper Vistula River	Vistula Delta
11th–15th centuries	96	82	N/A	46	112	19	16	51
16th century	245	84	67	47	88	39	19	36
17th century	168	169	39	13	31	44	11	29
18th century	162	187	31	26	39	30	3	16

In addition to the results distinguished for Poland, to evaluate the coherence between floods in Poland with other countries, results were compared with floods in Austria, Czechia, and Germany (Glaser & Stangl, 2003; Mudelsee et al., 2003; Glaser & Stangl, 2004; Brázdil et al., 2005a; Mudelsee et al., 2006; Rohr, 2006; Brázdil & Kirchner, 2007; Rohr, 2007; Brázdil et al., 2011; Blöschl et al., 2020). While considering this comparison, it is important to remember that it may be biased because of differences in the availability and reliability of sources, the number of rivers in the mentioned countries, and differences in how floods are distinguished.

Figure 19 shows the comparison of 40-year frequencies of floods in Poland, Austria, Czechia, and Germany. Evaluation of Fig. 19 reveals that the frequency of floods in Germany and Poland is greater than those in Austria and Czechia. In general, floods are more frequent in Poland than in the other countries, except in the three periods of 1601–1640, 1721–1760, and 1761–1800, when floods were more common in Germany. Before the 17th century (in Germany before 1680), there was a good consistency among all series, demonstrating a consistent rise in the frequency of floods, which is closely linked to the increasing availability of historical records. Nevertheless, this pattern has changed by the 17th century, when there are variations in flood occurrences in the analyzed flood data. In Poland, the most flood-rich periods were in 1557–1579, 1585–1596, 1646–1681, and 1692–1746 (see Table 2), whereas in Germany the flood-rich periods were 1641–1680 and 1721–1760. A relatively great number of floods occurred in the later part of the period in Czechia, while Austria also had a comparatively high number (Fig. 19). For all the countries, the most flood-rich period occurred between 1561 and

1600. According to statistical analyses, of the floods that occurred in Poland, around 53% also occurred in Germany, 35% in Czechia, and 18% in Austria.

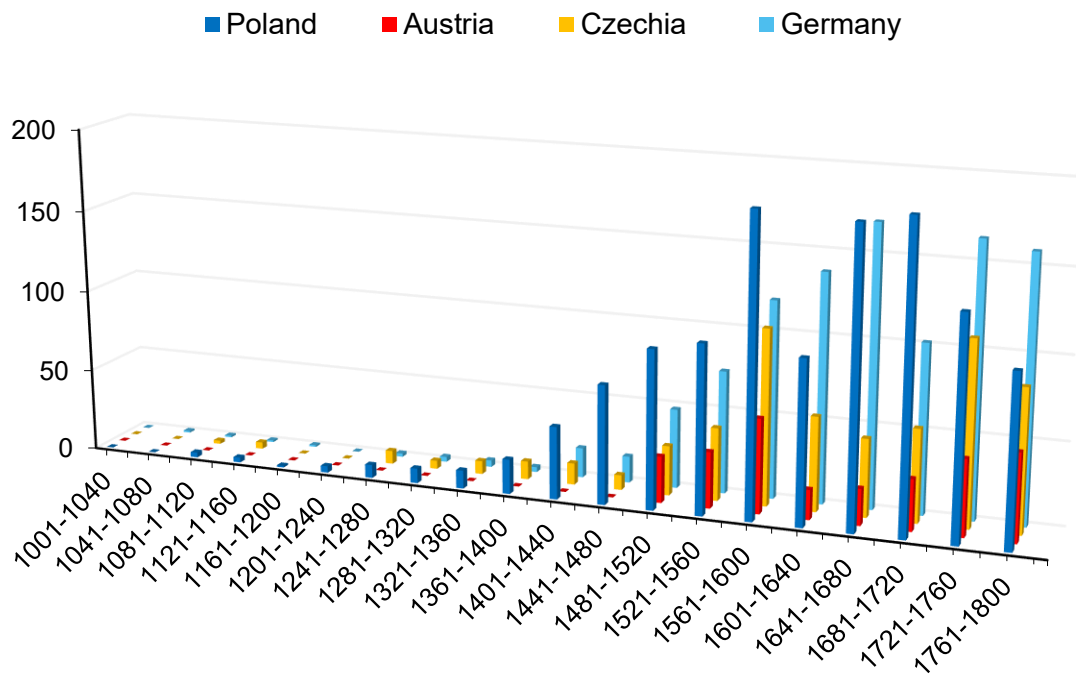


Fig. 19. 40-year flood frequencies in Poland, Austria, Czechia, and Germany in 11th–18th centuries (source: **P4**, updated)

Furthermore, using the MK test for the 16th–18th centuries, the statistical significance of trends for floods in Poland, Germany, Austria, and Czechia was determined (Fig. 20). The findings showed that, although there were rising statistically significant trends ($p\text{-value} < 0.05$) in Germany and Czechia, there was no statistically significant trend ($p\text{-value} > 0.05$) in Poland or Austria. Besides, relatively similar trends were seen for the years 1501–1800 when the moving 30-year trends in flood frequency in Poland (Fig. 17) determined in this analysis were compared with trends given for Central Europe by Glaser et al. (2004) (see their Fig. 2).

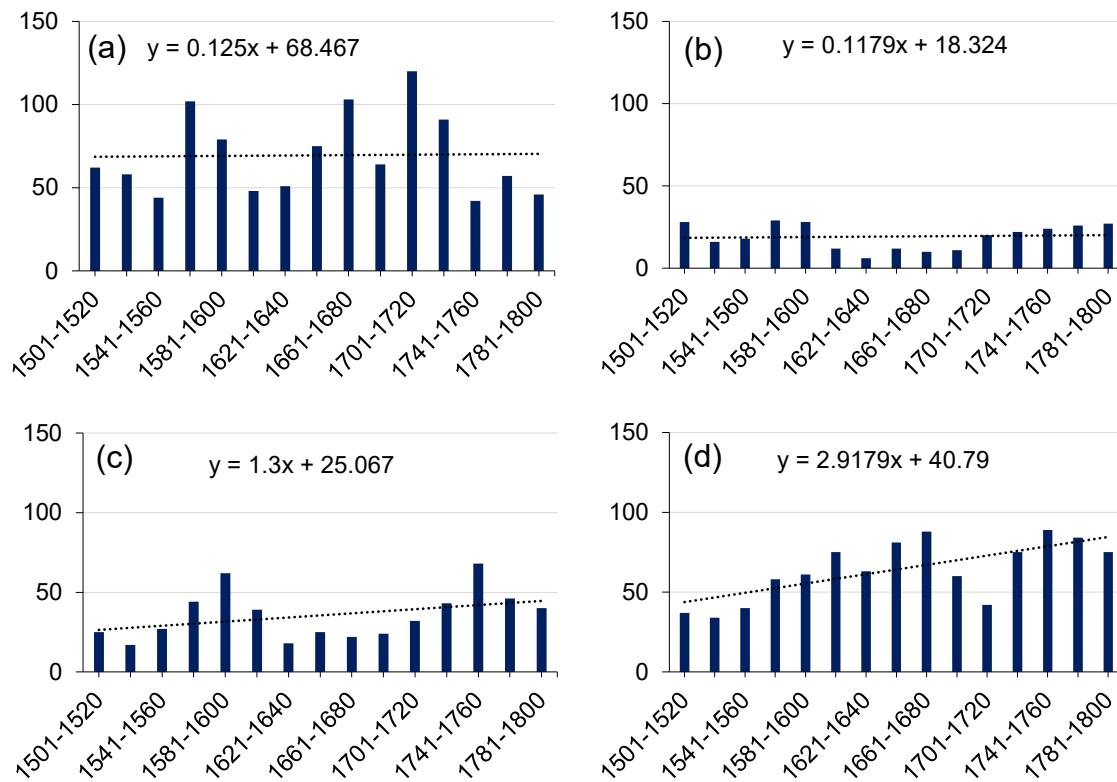


Fig. 20. 20-year frequencies of floods and their trends in (a) Poland, (b) Austria, (c) Czechia, and (d) Germany for the period 1501–1800 (source: **P4**, updated)

Because of their catastrophic effects, identifying and comprehending extreme floods is crucial for assessing the intensity of floods. Thus, in this study, the frequencies of extreme floods that occurred in Poland (this research) between 1001 and 1800 were compared to those that were available for Poland, Germany, and Czechia (Brázdil et al., 1999; Mudelsee et al., 2003; Brázdil & Kirchner, 2007; Elleder, 2015; Blöschl et al., 2020). Based on this comparison, it was revealed that Kowalewski (2006) distinguished 87 extreme floods, while these numbers were 257 and 347 based on the Barriendos and Coeur (2004) (category 2) and Brázdil et al. (2006b) (category 3) classifications in this study, respectively. Moreover, the number of extreme floods that occurred in Germany and Czechia (119 versus 72) was less than in Poland.

Based on the investigation of regional variations in floods in Poland during the historical period, results showed that the region of Silesia had the highest number of floods (553, 43%), while Masuria-Podlasie had the lowest number (11, ~1%). The primary reason for this is that Silesia has more historical sources available than other regions. Moreover, the Silesia region is surrounded by mountains and the river density is high in this region. Since the Oder River basin contains practically all of the Silesian region, floods in the Oder River basin were more frequent than in the Vistula River basin.

There is evidence that human-induced climate change has increased the occurrence of extreme events such as floods around the world in recent decades (Tabari, 2020b; Alifu et al., 2022; Rohde, 2023). According to this research findings, Poland has seen an increase in the frequency of floods since the end of the Little Ice Age (Fig. 17). Due to the high frequency of floods seen in the first 40 years of the 20th century, the trend's sign turned to negative for that century (see Fig. 17). It is important to note, however, that in the last 30 years of the 20th century, there was a change in flood trends and more floods have been observed. As a result, the tendency in recent decades has shifted and changed to positive. Thus, this tendency is in line with the changes seen in the majority of the world's regions.

It was extremely difficult to establish and demonstrate potential direct meteorological or climatological causes for flood occurrences before the 19th century due to inadequate observation data. However, it is expected that this effort will help in understanding the different features of flood frequencies (and causes) in Central Europe, particularly in Poland.

Conclusions

Increasing global warming's impact on human life has caused significant concerns for human society and consequently encouraged researchers to investigate various extreme events in depth. In the investigation of extreme phenomena, the lack of sufficient data before the pre-industrial period is an obstacle to evaluating these extreme events. Thus, studies of extreme events, such as floods, particularly before the 19th century, will help the scientific communities to expand their studies and achieve better results and greater understanding of flood events. This research undertook a deep and comprehensive assessment to try to fill the knowledge gap in studies about floods in Central Europe before the 19th century, specifically in Poland.

In the assessment of floods, based on the documentary evidence, inherent biases in these data may lead to uncertainties in the results. In addition, there is a relatively direct connection between the availability of sources and the frequency of floods. For example, in the medieval period (11th–15th centuries), the results may not be the exact results of flood frequency due to the lack of sufficient documentary evidence for this period. However, from the 16th century onwards, the availability of sources leads to relatively realistic results in terms of flood frequency.

The main advantage of this research that distinguishes it from previous studies is the cooperation with historians. This cooperation allowed us to obtain comprehensive and reliable datasets of floods by providing access to a greater number of sources and especially to good-

quality sources. Another important fact regarding this research is that it provides a reliable comparison of flood frequency in Poland with some other countries in Central Europe.

The main findings of this research are provided below:

1. 1,680 floods were documented in Poland during the last millennium, while 1,252 occurred during the pre-instrumental (historical) period (1001–1800).
2. Floods in Poland in the historical period were most common in the Oder River basin (55% cases), followed by the Vistula River basin (43% cases).
3. The regions with the highest percentage of floods between 1001 and 1800 were Silesia (43%), the Baltic Coast and Pomerania (23%), and Lesser Poland (17%).
4. The most prevalent flood intensities, at 33% and 70%, respectively, were category 2 (“above-average, or supra-regional flood”) following Brázdil et al. (2006) and category 1 (“extraordinary”) using Barriendos and Coeur (2004).
5. The highest and lowest numbers of floods (46% and 8%) occurred in the summer and autumn, respectively.
6. The origin of 60% of floods in Poland in 1001–1800 was identified; among those, rain was the main cause, accounting for 44%.
7. Poland's flood frequencies showed a statistically significant trend of decline from 1501 to 2000 and an increase from 1801 to 2000. In terms of statistics, the trend for 1501–1800 was negligible.
8. Floods were more common in Poland and Germany than in Czechia and Austria in the period 1001–1800.

As recommendations for future studies, it is suggested that extreme floods in Poland before the contemporary era be investigated in detail, in particular, due to their serious social and economic consequences. For example, reconstructions of individual major floods (spatial coverage, nature and scale of damage, etc.) for which more detailed descriptions exist would be extremely useful. It would also be advisable to assess the credibility of the description of these floods, for example, using the method presented in the work of Magnuszewski & Gutry-Korycka (2009). Also, many studies (Kundzewicz et al., 2018; Mezghani et al., 2019; Pińskwar & Choryński, 2021), including one study by Ghazi et al. (2023c), have projected that precipitation and the days with extreme precipitation will rise in Poland by the end of the 21st century. Therefore, it is recommended that the projection of future occurrences of floods for the area of Poland be investigated in future studies based on state-of-the-art simulation of climate models, to provide valuable and detailed information for the public and policymakers.

Code and data availability

Figure 1 was created in ArcGIS 10.8.2 software environment. The 3D map of Poland was created using the rayshader package in R-studio based on a tutorial provided by Dr. Milos Popovic (www.milospopovic.net). The database of floods in Poland in 11th–15th centuries (<https://doi.org/10.18150/WD18XJ>), 16th century (<https://doi.org/10.18150/T3RXRI>), 17th–18th centuries (<https://doi.org/10.18150/VLPAFG>) and 11th–18th centuries (<https://doi.org/10.18150/VLTVD9>) are freely available to the public.

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