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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

Prof. Dr. hab. Rajmund Przybylak

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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 *journal name* (ISSN)	Impact factor	Points (MNiSW)
P1	The frequency, intensity, and origin of floods in Poland in the 11th–15th centuries based on documentary evidence **Babak Ghazi***, Rajmund Przybylak, Piotr Oliński, Katarzyna Bogdańska, Aleksandra Pospieszyńska (https://doi.org/10.1016/j.jhydrol.2023.129778)	2023 *Journal of Hydrology* (0022-1694)	6.4	140
P2	An assessment of flood occurrences in Poland in the 16th century **Babak Ghazi**, Rajmund Przybylak, Piotr Oliński, Waldemar Chorążyczewski, Aleksandra Pospieszyńska (https://doi.org/10.1016/j.ejrh.2023.101597)	2023 *Journal of Hydrology: Regional Studies* (2214-5818)	4.7	100
P3	A comprehensive study of floods in Poland in the 17th–18th centuries **Babak Ghazi**, Rajmund Przybylak, Piotr Oliński, Michał Targowski, Janusz Filipiak, Aleksandra Pospieszyńska (https://doi.org/10.1016/j.ejrh.2024.101796)	2024 *Journal of Hydrology: Regional Studies* (2214-5818)	4.7	100
P4	Flood occurrences and characteristics in Poland in the last millennium **Babak Ghazi**, Rajmund Przybylak, Piotr Oliński, Aleksandra Pospieszyńska	2024 Submitted to *Scientific Reports* (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 *Water* (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 *Scientific Reports* (2045-2322)	4.6
3	Projection of future meteorological droughts in Lake Urmia Basin, Iran (https://doi.org/10.3390/w15081558)	2023 *Water* (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 *Climate* (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 *Theoretical and Applied Climatology* (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 *Arabian Journal of Geosciences* (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 *Groundwater for Sustainable Development* (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 *Environmental Earth Sciences* (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 *Arabian Journal of Geosciences* (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/VLTVD9).

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 17^{th}–18^{th} 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 19^{th} century) with those after this period (19^{th}–20^{th} 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-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 dotykały 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%) zapisek 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/VLPAFG
- 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.

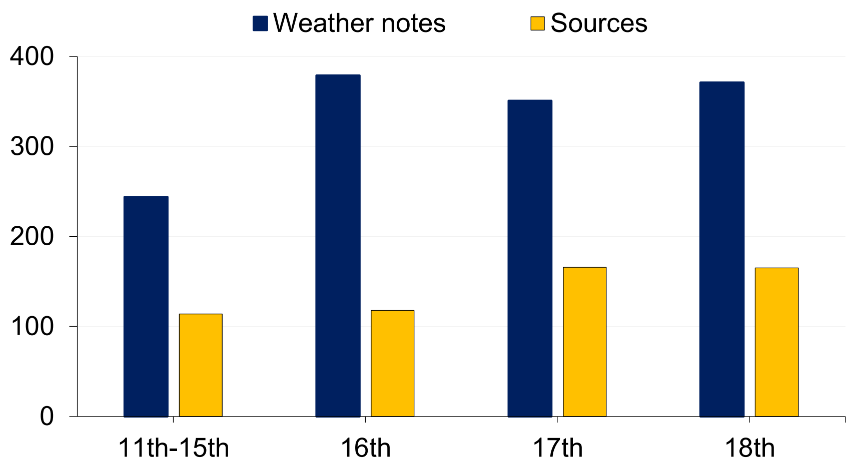

Fig. 2. Number of used sources and weather notes to assess floods in Poland in the period 1001–1800 (source: **P4**, updated)

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).

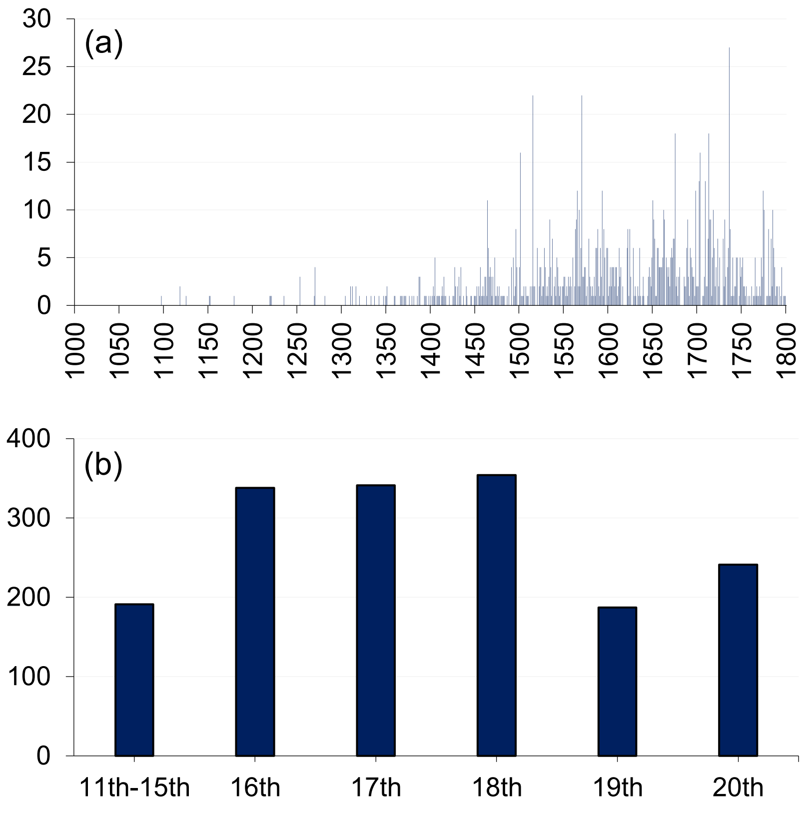

Fig. 3. Number of floods in Poland (a) annual frequency for the 11th–18th centuries and (b) flood occurrences in different centuries in Poland (11th–20th centuries) (source: **P4**, updated)

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.

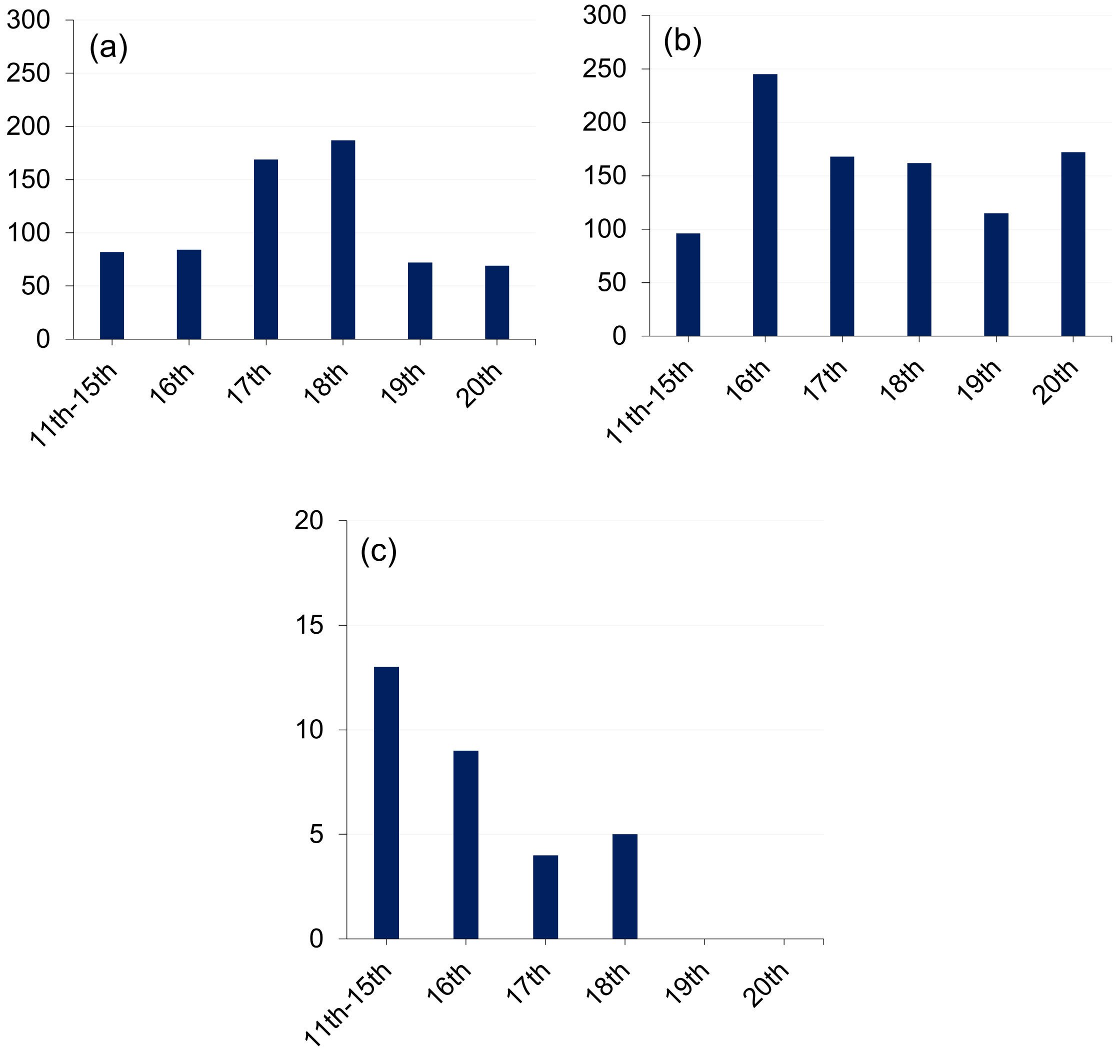

Fig. 4. Number of floods in Poland in the 11th–20th centuries in (a) the Vistula River basin, (b) the Oder River basin, and (c) the Baltic Coast rivers basin (there is no data for floods in the 19th and 20th centuries for this area) (source: **P4**, updated)

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

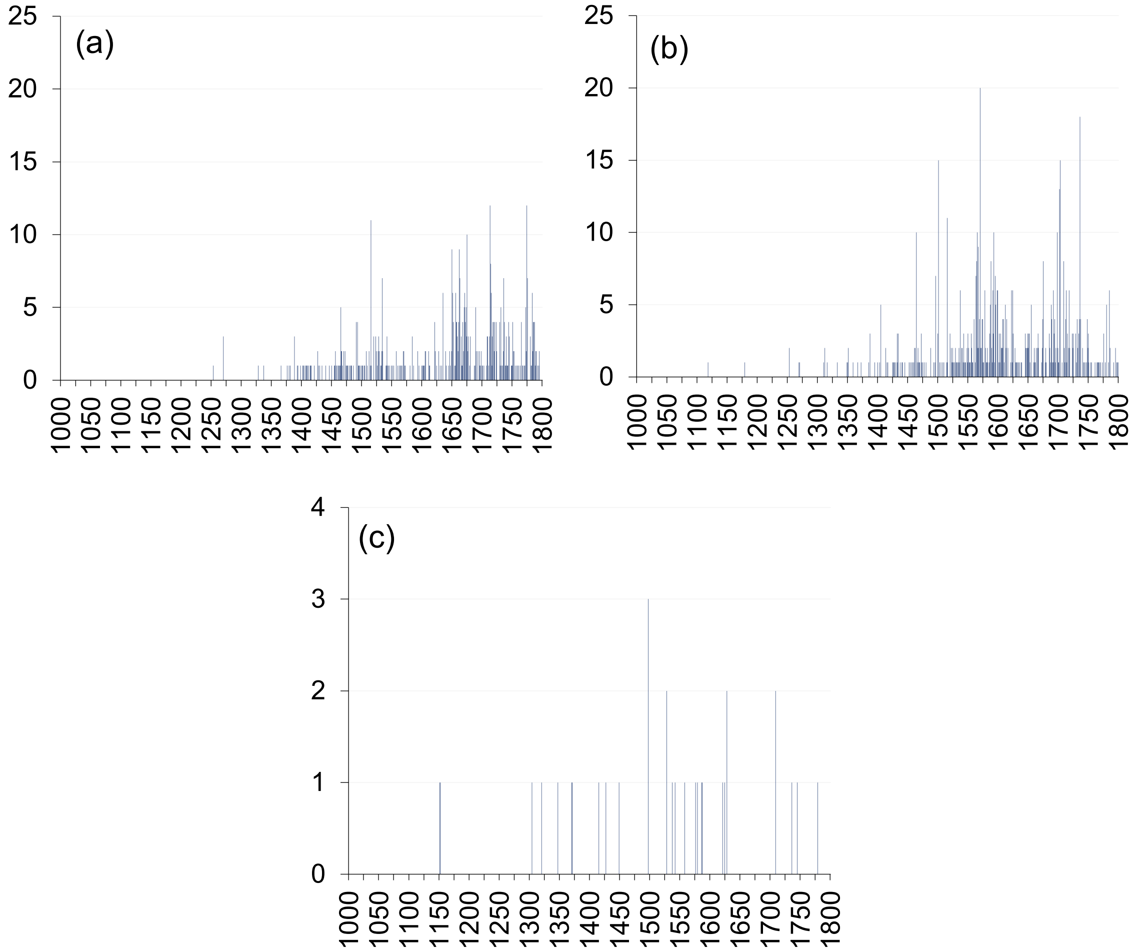

Fig. 5. Annual number of floods in Poland, AD 1001–1800: (a) Vistula River basin, (b) Oder River basin, and (c) Baltic Coast rivers basin (source: **P4**, updated)

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	–

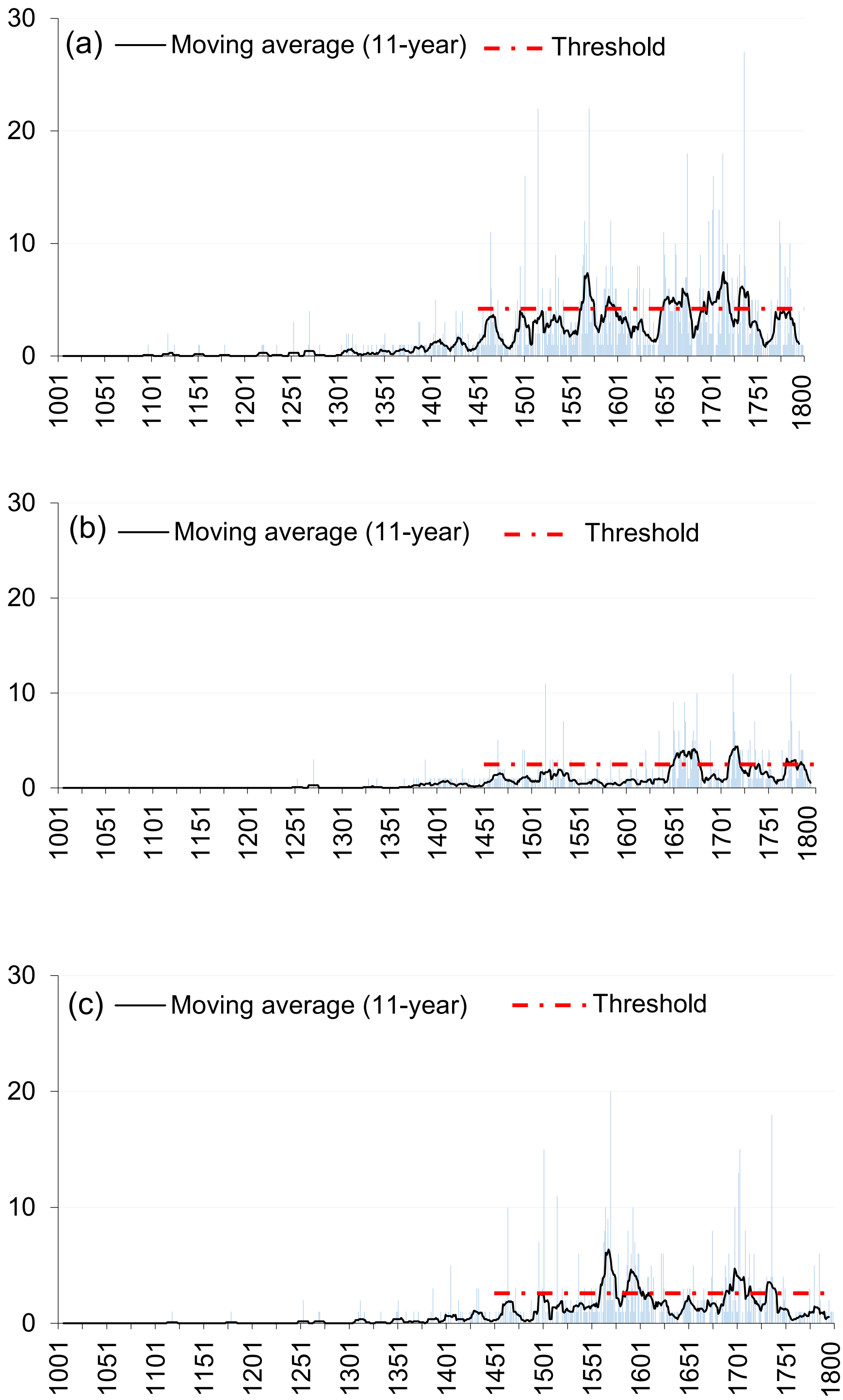

Fig. 6. Annual (bars) and 11-year mean (black line) frequencies of floods in the period 1001–1800 in (a) all of Poland, (b) the Vistula River basin, and (c) the Oder River basin with an indication of flood-rich periods (years above red lines)

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."

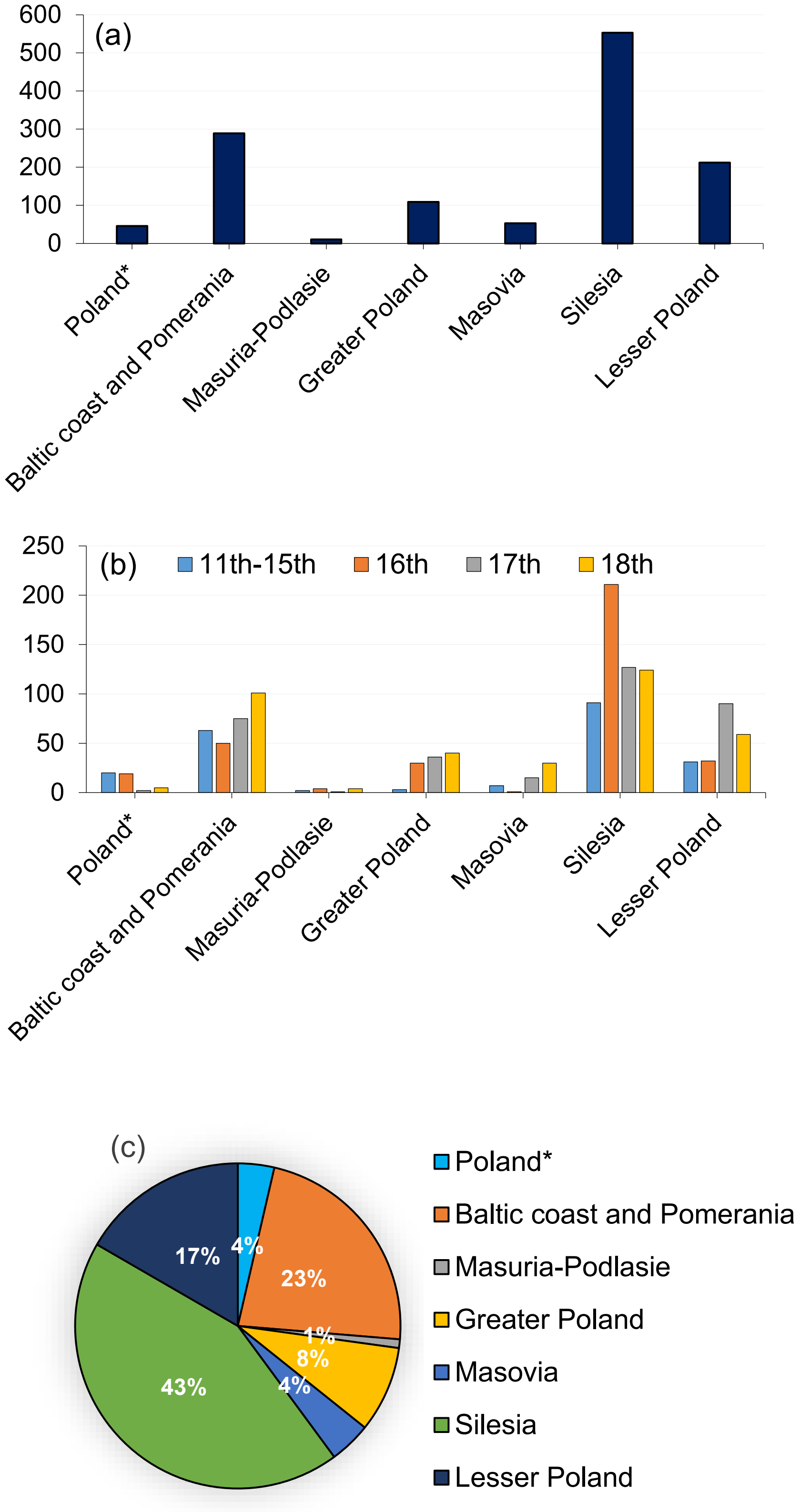

Fig. 7. Number of floods in Poland in 1001–1800; (a) floods in different regions, (b) floods in different sub-periods and regions (c) floods by percent for different regions (source: **P4**, updated)

*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).

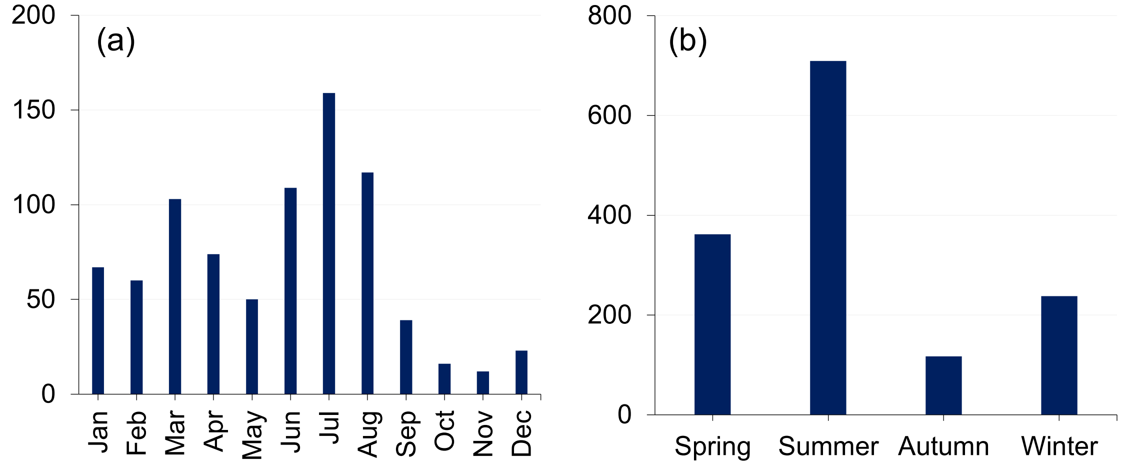

Fig. 8. Number of floods in Poland in the 11th–18th centuries (a) monthly and (b) seasonal (source: **P4**, updated)

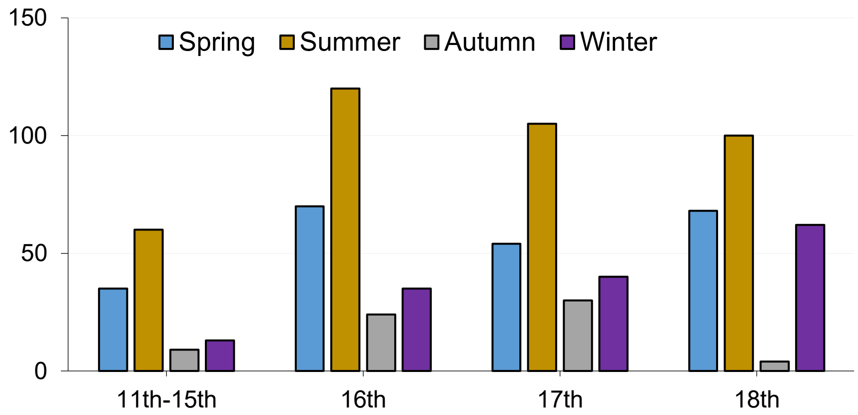

Fig. 9. Number of floods in Poland in the different centuries based on the season (source: **P4**, updated)

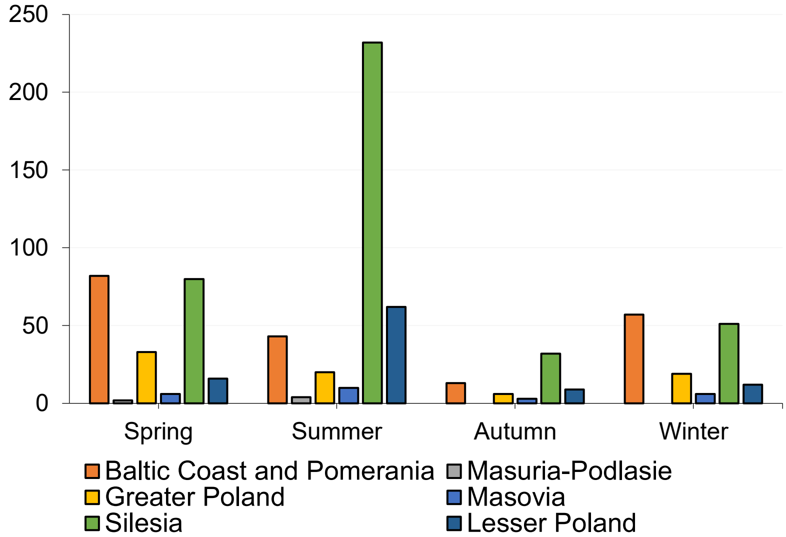

Fig. 10. Seasonal frequency of floods in the main six regions of Poland, 1001–1800 (source: **P4**, updated)

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.

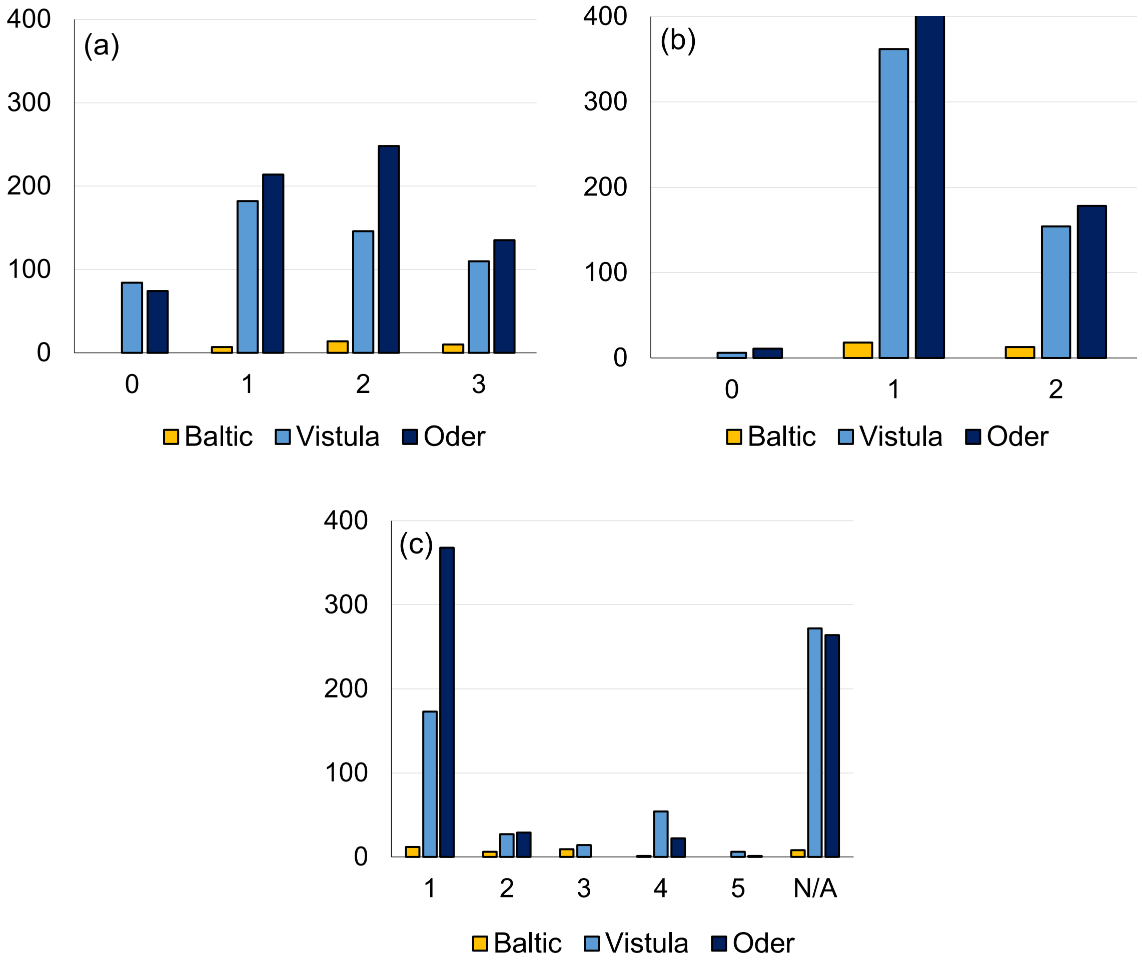

Fig. 11. Number of floods in the river basins of Poland in the 11th–18th centuries based on (a) Brázdil et al. (2006), (b), Barriendos & Coeur (2004) and (c) Lambor (1954) classifications (source: **P4**, updated)

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.

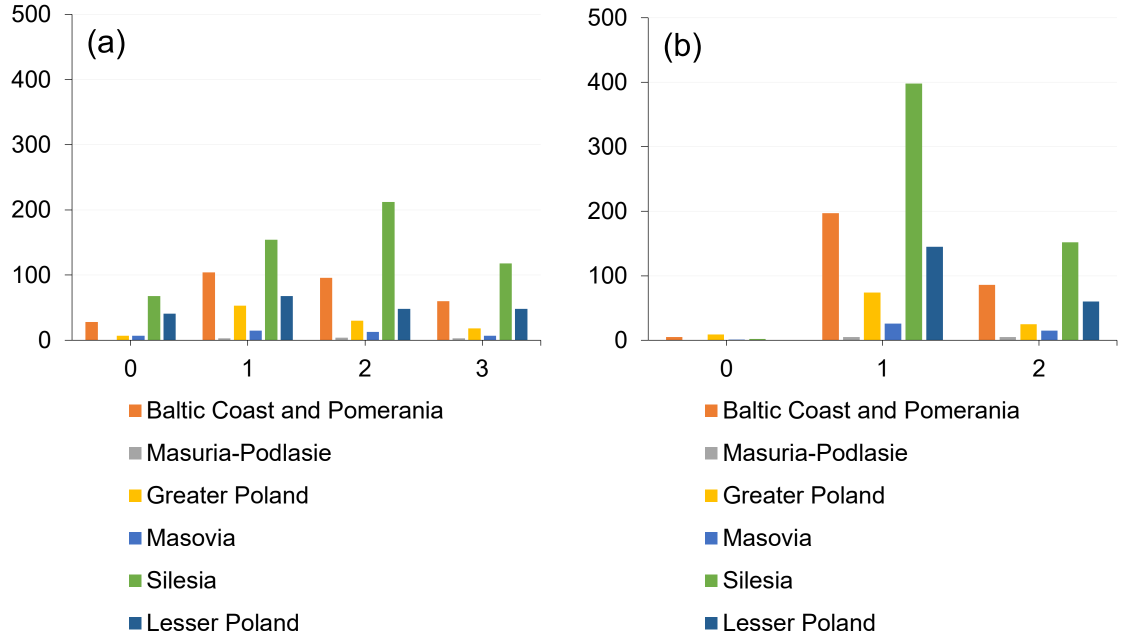

Fig. 12. Classification of flood intensity based on (a) Brázdil et al. (2006), and (b), Barriendos & Coeur (2004) for the main six regions of Poland (source: **P4**, updated)

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 11^{th}–18^{th} centuries. The highest contribution of rain to flood occurrences was in the 16^{th} century and the lowest was in the 18^{th} century. The contribution of "snowmelt" and "winter" was relatively higher in the 18^{th} century than in other sub-periods, while in the 11^{th}–15^{th} 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).

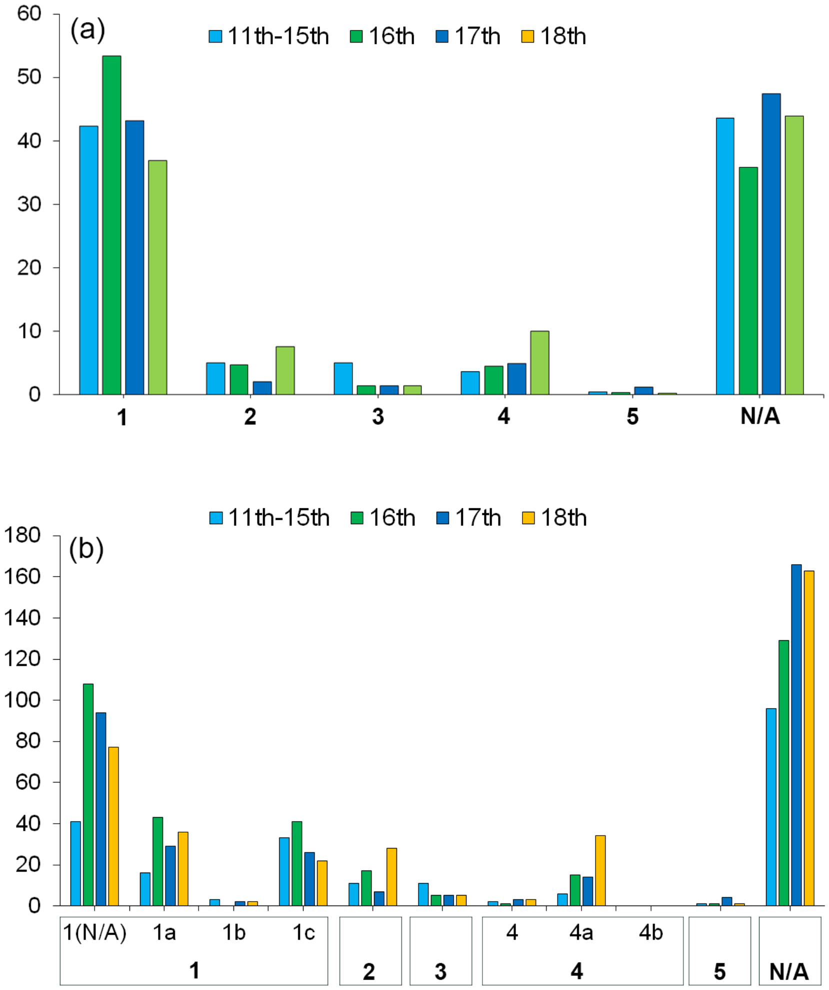

Fig. 13. Frequency of type of origin of floods in Poland in the period 11th–18th centuries (a) relative frequency based on Lambor's (1954) classification (b) number of floods

*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%).

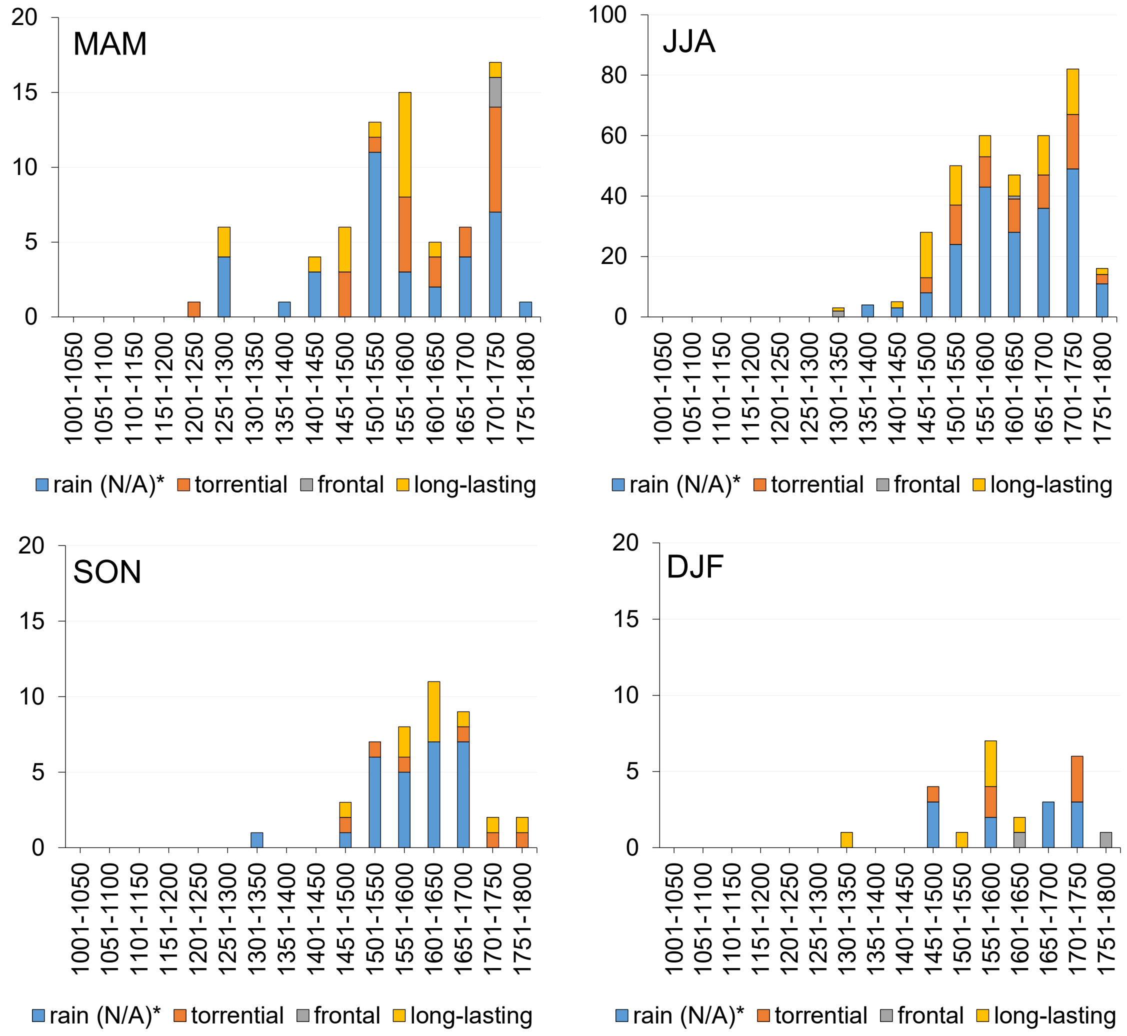

Fig. 14. Seasonal (MAM, JJA, SON, DJF) flood frequencies in Poland in the period 1001–1800 caused by rain and its subtypes (source: **P4**, updated), please note the scale difference for summer (JJA)

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)
11th–15th 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)
16th 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)
17th 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
18th 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

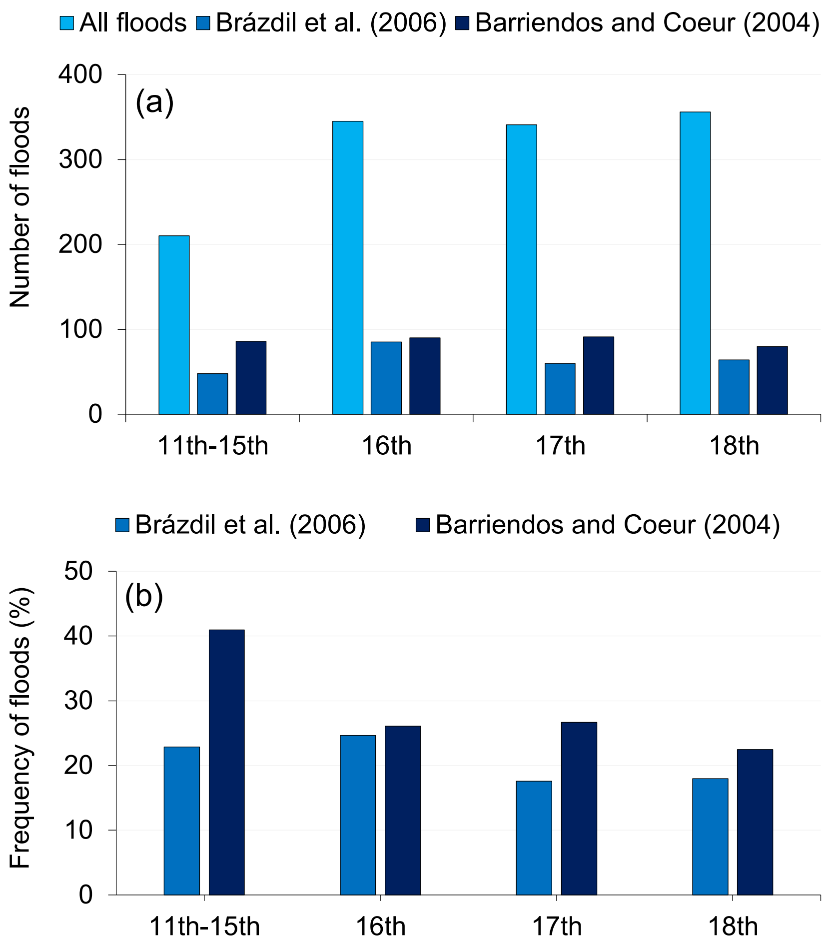

Fig. 15. (a) Number of all floods and extreme floods ("category 3" in Brázdil et al., 2006, and "category 2" in Barriendos & Coeur, 2004) for Poland in the study sub-periods, (b) Percentage share of extreme floods relative to all floods

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), Boleslawiec (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.

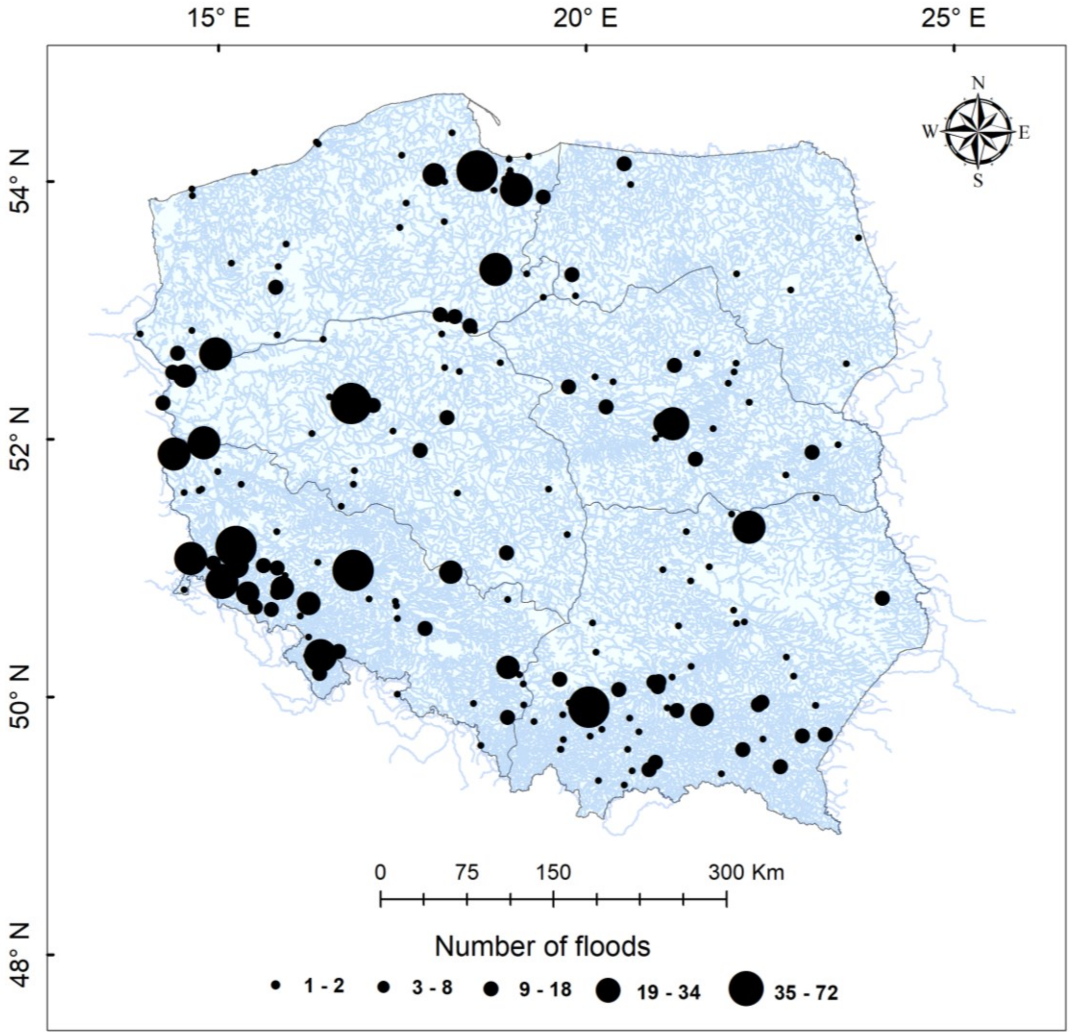

Fig. 16. Spatial distribution and frequency of floods in Poland in the 11th–18th centuries (source: **P4**, updated)

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-value > 0.05), while there is an increasing and decreasing statistically significant trend (p-value < 0.05) for the periods of 1801–2000 and 1501–2000, respectively.

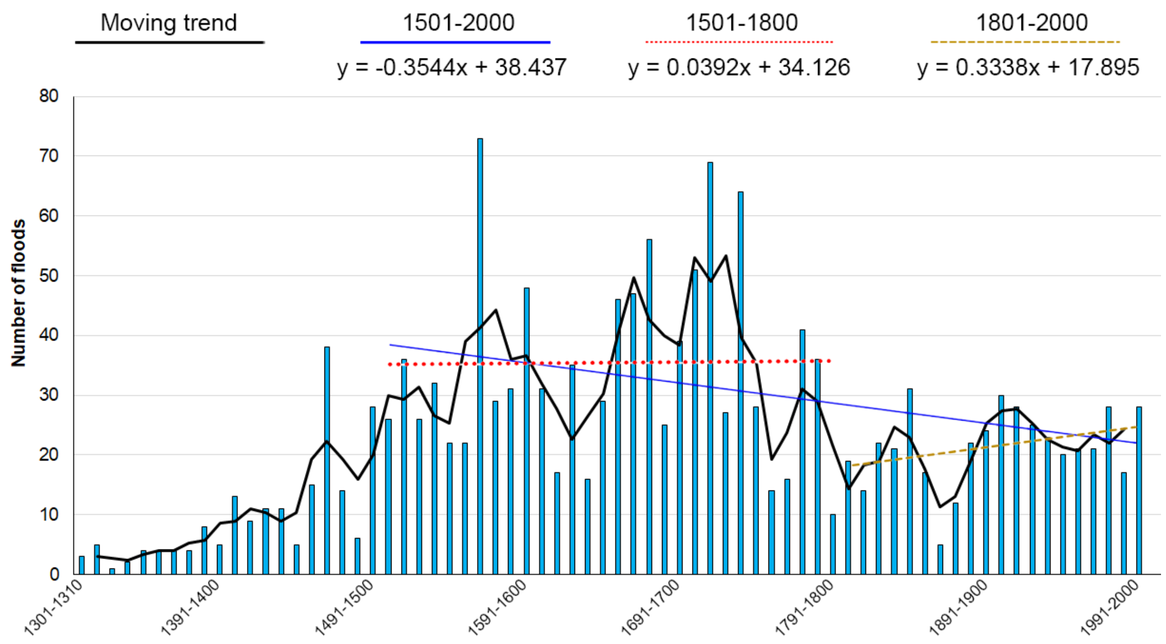

Fig. 17. Change in decadal (bars) and moving 3-decadal means (black line) flood frequencies in Poland from AD 1301–2000 and their long-term trends (color lines) (source: **P4**, updated)

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.

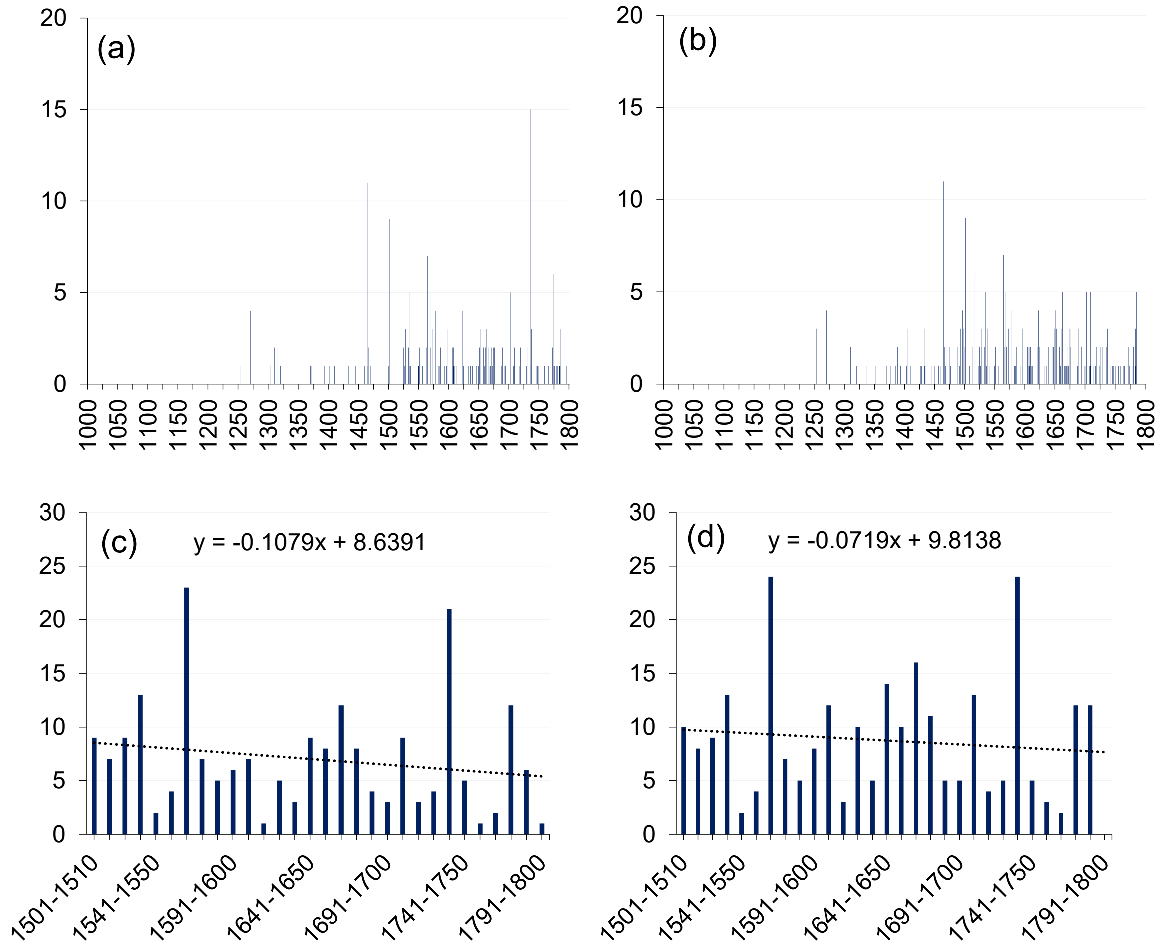

Fig. 18. Annual (a, b) and decadal (c, d) frequency of extreme floods in Poland in the 11th–18th centuries (source: **P4**, updated)

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.

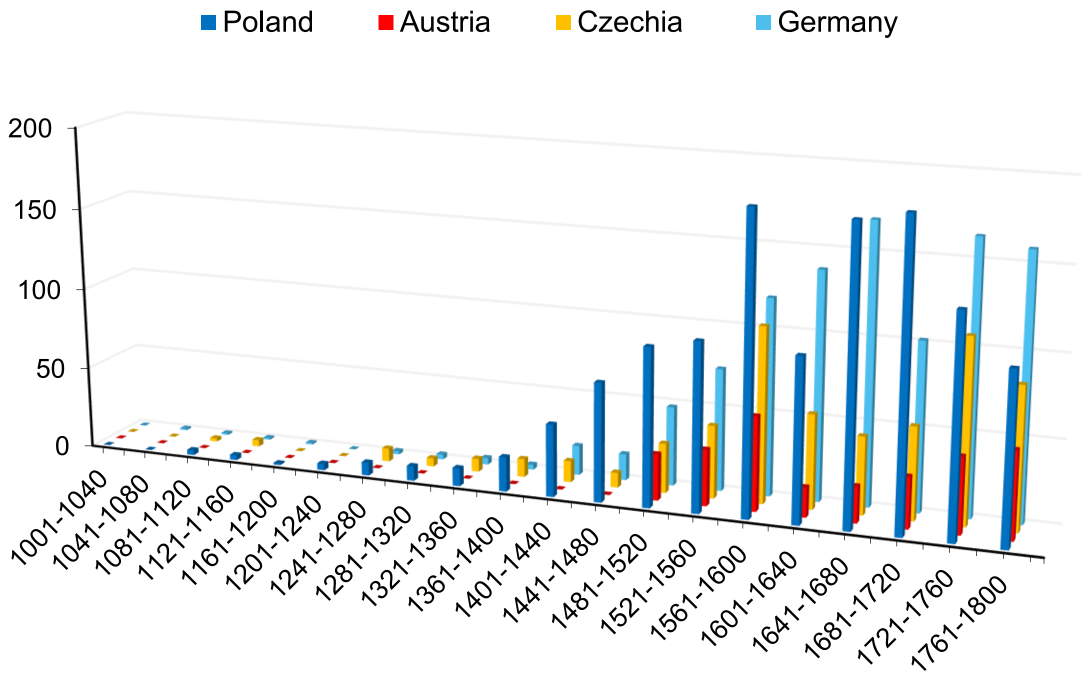

Fig. 19. 40-year flood frequencies in Poland, Austria, Czechia, and Germany in 11th–18th centuries (source: **P4**, updated)

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-value < 0.05) in Germany and Czechia, there was no statistically significant trend (p-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).

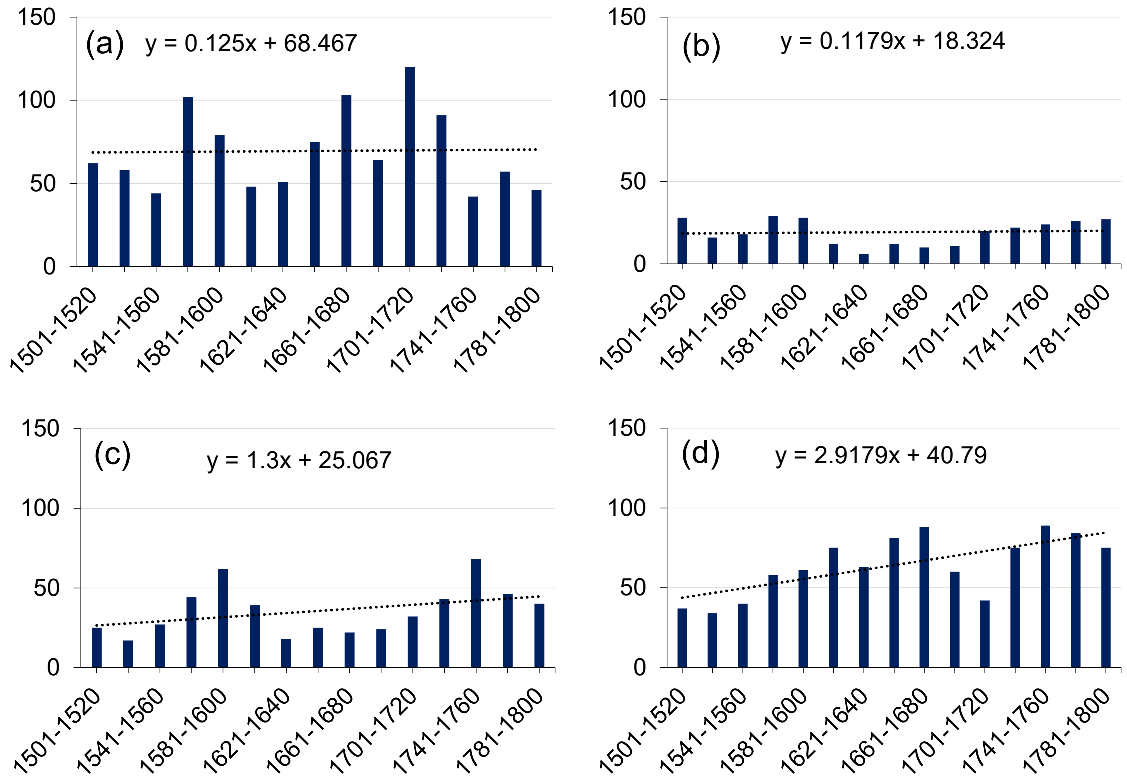

Fig. 20. 20-year frequencies of floods and their trends in (a) Poland, (b) Austria, (c) Czechia, and (d) Germany for the period 1501–1800 (source: **P4**, updated)

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 11^{th}–15^{th} centuries (https://doi.org/10.18150/WD18XJ), 16^{th} century (https://doi.org/10.18150/T3RXRI), 17^{th}–18^{th} centuries (https://doi.org/10.18150/VLPAFG) and 11^{th}–18^{th} centuries (https://doi.org/10.18150/VLTVD9) are freely available to the public.

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Appendix 1: Supplementary materials

Table S1: Classification of floods based on intensity (Brázdil et al., 2006b) and (Barriendos & Coeur, 2004)

Source	Index	Index Classification	Description
(Brázdil et al., 2006b)	0	Flood	No additional reports
	1	Smaller, regional flood	Little damage, e.g. riverside fields and gardens; wood supplies. Short duration of flooding
	2	Above-average, or supra-regional flood	Damage to water-related buildings and constructions. Flood of average duration, severe damage to riverside fields and gardens; loss of animals, and sometimes human lives.
	3	Above-average, or supra-regional flood on a disastrous scale	Severe damage to water-related buildings and constructions. Some buildings are completely destroyed or torn away by the flood. Longer flood duration: days or weeks; severe damage to riverside fields and gardens; extensive loss of animals and people
Barriendos & Coeur (2004)	0	ordinary	In-bank flow, no damage, water discharge can increase but without overflowing
	1	extraordinary	Overflowing of river bed, damage but no destruction. Flood without destruction
	2	catastrophic	Overflowing of river bed, destruction of permanent infrastructure. Flood with general damage and destruction.

Table S2. Classification of floods based on origin (Lambor, 1954)

Source	Index	Description
(Lambor, 1954)	1 (1a, 1b, 1c)	1 – rain, subtypes: 1a – torrential rains, 1b – frontal rains, 1c – long-lasting, territorially widespread rains,
	2	snowmelt
	3*	storm
	4 (4a, 4b)	winter, subtypes: 4a – ice jam, 4b – shuga
	5	anthropogenic

* "Storm" category belongs to floods that occurred on the coast of the Baltic Sea and is mainly caused by strong (gale) winds.

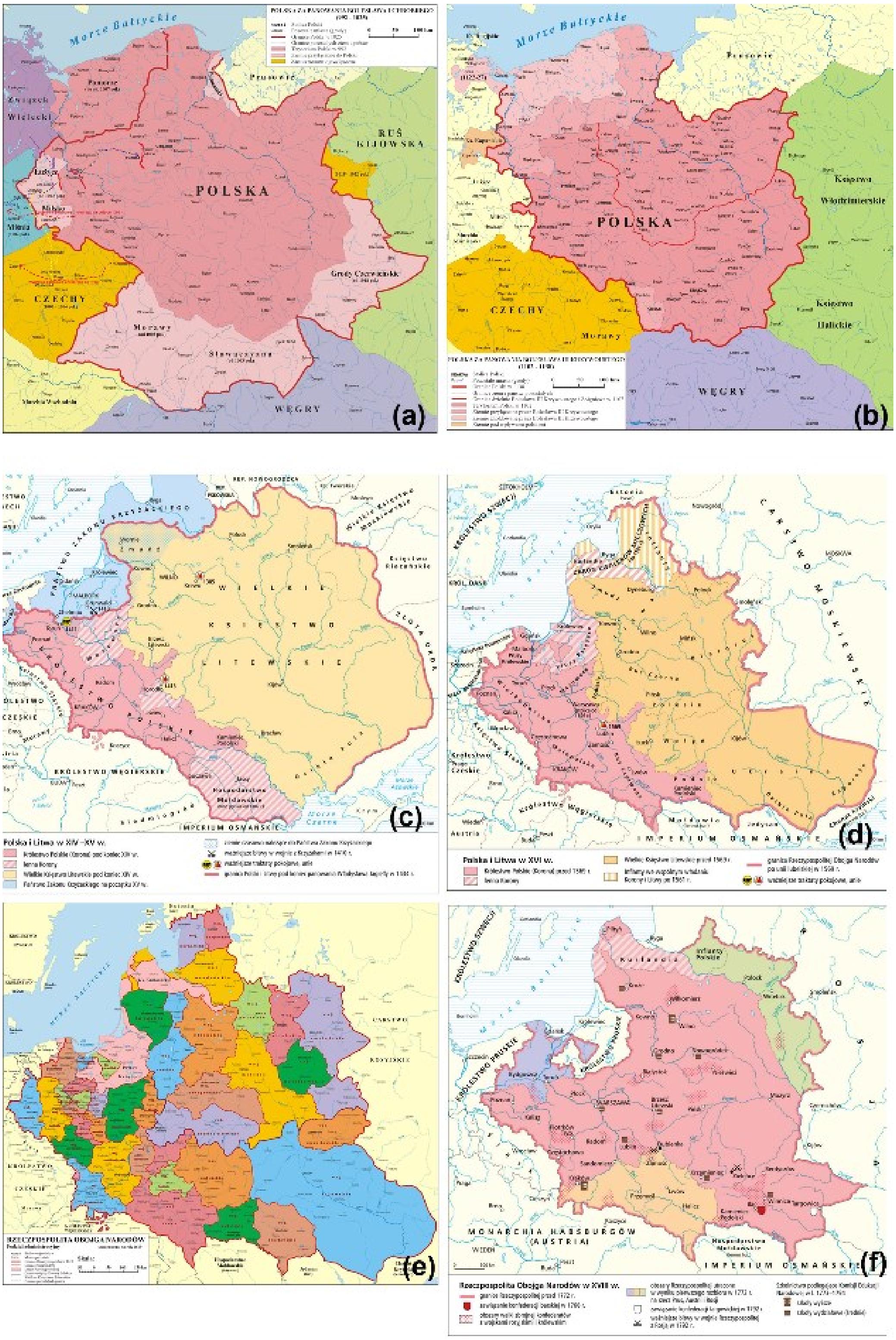

Fig. S1. Changes in the borders of Poland, (a) 992–1025 period (red line, the year 1025), (b) 1102–38 period, (red line, the year 1138), (c) 14th and 15th centuries (red line, the year 1434), (d) 16th century (pink line, the year 1569), (e) 17th century, and (f) 18th century (pink line, the year 1772) sources: (http://wlaczpolske.pl/index.php?etap=10&i=1242&nomenu=1&oe, https://en.m.wikipedia.org/wiki/File:Dzia%C5%82ania_podczas_wojny_polsko_niemieckiej_1002-1005.png, https://en.m.wikipedia.org/wiki/File:Polska_1102_-_1138.png, https://commons.wikimedia.org/wiki/File:Podzia%C5%82_administracyjny_I_RP.png)

Appendix 2: Scientific publications

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Contents lists available at ScienceDirect

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Research papers

The frequency, intensity, and origin of floods in Poland in the 11th–15th centuries based on documentary evidence

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ABSTRACT

Documentary evidence is increasingly being recognized as a precious source for assessing flood records. We have used this type of proxy data to identify the occurrence of floods in Poland from the 11th to the 15th centuries. In addition, we estimated the intensity of each flood event using the best-known classifications for Europe (Barriendos and Coeur, 2004; Brázdil et al., 2006) and assessed their origin based on modified Lambor's (1954) criteria. The database of floods in Poland contains 166 occurrences in the study period. Most occurred in the 15th century (61.4%). Of the studied regions, Silesia and the Baltic Coast and Pomerania regions were the two most affected by flood events, each accounting for 33–34% of instances. Based on the Brázdil et al. (2006) classification, 77 of the recorded floods are above-average or supra-regional. Also, the indexation of floods based on Barriendos and Coeur (2004) demonstrated that 99 were extraordinary flood events. Rain and its subtypes were the leading causes of floods, with 79 records (47.6%). Flood occurrence in Poland exhibited good spatial coherency with neighboring countries. The updated and most complete inventory of floods in medieval Poland that we present here with a detailed analysis of their frequency, intensity and origin, improves the existing knowledge about this phenomenon in Central Europe. The results of this study, similarly to many other previous studies, also confirm the great capacity for documentary evidence to provide valuable and reliable information about flood records for the pre-instrumental period.

1. Introduction

In recent decades, climate change has intensified, increasing the global number of extreme hydrometeorological events, such as floods and droughts (IPCC, 2013, 2021). Floods are among the most frequent, fatal, and costly types of natural disasters and affect all aspects of life, including agriculture, industry, education, and humans (Brázdil et al., 2006; UNISDR, 2015). Floods cause tens of thousands of deaths, affect hundreds of millions of people, and cause tens of billions of dollars' worth of damage every year (Field et al., 2012; Méndez-Lázaro et al., 2014). So too in Poland, floods are the main natural disaster. In recent decades, material losses associated with floods have been very high, and for the dramatic flood in the summer of 1997 reached USD 2.3–3.5 billion (Kundzewicz et al., 1999). These impacts show the vulnerability of different regions worldwide to floods, emphasizing the need to improve the knowledge upon which we assess the frequencies, intensities, and occurrences of floods (Blöschl et al., 2013; Wilhelm et al., 2019). Therefore, the long-term study of floods is necessary to comprehend them as natural phenomena and associated with anthropogenic activities.

An issue of increasing concern to public and scientific institutions is the need to comprehend flood events and their variations over time (Hall et al., 2014). This issue remains extremely difficult to address due to various human-related errors in instrumental data measurement at gauging stations and the lack of sufficient instrumental data for past centuries (Hall et al., 2014; Merz et al., 2014). Knowledge about floods can also be retrieved from historical and documentary sources (Glaser & Stangl, 2004). Documentary evidence covering a long time span can provide comprehensive and detailed information regarding changes in the frequencies and intensities of flood events (Brázdil et al., 2006; Glaser et al., 2010). Also, understanding the nature of historical catastrophic floods can help to improve awareness of flood risk and give

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policymakers clear insight that supports the development of various mitigation policies (Cœur & Lang, 2008). Floods, being the most impactful of natural disasters, were very often mentioned in different written sources such as chronicles, annals, diaries, memoirs, pamphlets, accounting books, official books, technical reports, weather journals, newspapers, memorial books, journals, flood maps, photos (photographs, paintings, and engravings) and others (Brázdil et al., 2006; Glaser et al., 2010).

In the current literature, both international and Polish, floods are a frequent research issue. A good review can be found in publications by, for example, Brázdil et al. (2006), Cyberski et al. (2006), Kiss (2019), and Tarasova et al. (2019). The Polish literature is usually limited to the period of instrumental observations – the last 200 years or so (Born, 1954; Mikulski, 1954; Makowski, 1994; Fal and Dąbrowski, 2001a, 2001b; Kotarba, 2004; Gutry-Korycka, 2010; Kuźniar, 2010; Zielonka et al., 2010; Magnuszewski et al., 2012; Kundzewicz et al., 2014; Kubiak-Wójcicka, 2014). Works covering longer periods than the last 200 years or reconstructing ancient historical floods are far fewer (Trzebińska and Trzebiński, 1954; Tyszka, 1954; Girguś and Strupczewski, 1965; Grześ, 1991; Cyberski and Kawińska, 1995; Mudelsee et al., 2003, 2004; Cyberski et al., 2006; Gutry-Korycka, 2007, 2010; Kubiak-Wójcicka, 2014; Pawłowski and Gorączko, 2014; Wosiewicz, 2017). Most of the publications cited above are written in Polish and are thus unknown to the international community. This is easily proven by a reading of the review works of Brázdil et al. (2006) and Tarasova et al. (2019) (section 3), which cite many examples of works analyzing the occurrence of floods in European countries in the last millennium that were published in the period 1985–2018. Unfortunately, the list of the many countries for which such works exist does not include Poland. The list of Polish publications cited above shows that, since the publication of the articles by Brázdil et al. (2006) and Cyberski et al. (2006), interest in such works has been growing. In spite of their unquestionably high value, what is striking is the rather mechanical listing of flood records, or that they indicate only those of the greatest scale. Furthermore, the criteria for delimiting extreme floods are usually not given. This kind of simplification, which results from the content of historical sources not having been analyzed in depth, has also resulted in a simplification of the statistical summaries given for historical times. The more detailed analysis of the sources and the more detailed description of individual floods that we make in the present paper has allowed for more precise statistical summaries and a more accurate assessment of flood frequency changes for Poland as a whole and for its regions.

For classification of floods intensities and causes, we utilized the propositions in papers by Lambor (1954), Barriendos and Coeur (2004), and Brázdil et al. (2006). Lambor (1954) classified the main causes of floods in Poland as torrential and frontal rain, snow melt, winter, and storm. He also described the possible time frame of occurrence of floods during the year. Barriendos and Coeur (2004) reviewed various flood event reconstructions in France and Spain in historical series from non-instrumental references and proposed a comprehensive flood classification based on scale, intensity, and destructive impact. They defined floods as ordinary, extraordinary, and catastrophic. Brázdil et al. (2006) slightly modified the classification of floods proposed by Sturm et al. (2001). They distinguished four categories; 0 for flood; 1 for small, regional flood; 2 for an above average or supra regional flood; and 3 for an above-average or supra-regional flood on a disastrous scale. See the next section for more detail.

Various studies based on documentary evidence have been conducted to assess flood frequency in Europe. Barriendos Vallve and Martin-Vide (1998) studied flood events in the central Spanish region and Catalonia in conjunction with climate variability during the 13th–20th centuries. The authors concluded that the documentary evidence has an important impact in demonstrating the sensitivity of flood extremes to changes in climatic variables. Mudelsee et al. (2003) presented long-term summer and winter flood records for the Oder and Elbe rivers in Central Europe. They mentioned that the number of floods on the Oder River from 1269 to 2002 was greatest in March (50) and smallest in November (only 3). Elleder (2015) studied the frequency of floods in the Vltava River basin in Prague. On the basis of documentary sources, the author estimated flood peak discharges for the pre-instrumental period of 1118–1824 using several approaches. The results showed that 187 such floods occurred during this time. He also researched the instrumental period from 1825 to 2013. Benito et al. (2021) used documentary sources, early water-level readings, and continuous gauge records of the Duero River in Zamora (Spain) to assess flood hazards. The results demonstrated that between 1250 and 1871, 69 floods occurred (38 ordinary, 16 extraordinary, and 15 catastrophic).

A literature review reveals a variety of studies analyzing different aspects of floods for many parts of the world. However, there is a clear knowledge gap in flood studies based on the documentary evidence prior to the 18th century. Most start in the 18th century or later. As mentioned above, the same is true of Poland. However, knowledge about the occurrence of floods all across Europe is particularly limited for before the 16th century due to the scarcity of written sources (see Fig. 2 in Glaser et al., 2010). According to the review paper of Glaser et al. (2010), most are also restricted to describing only severe or catastrophic events. For these reasons, detailed regional investigations of flood occurrences based on documentary evidence for this period are crucial. Comprehensive and more reliable knowledge of the long-term history of extreme hydrometeorological events is also necessary for the construction of reliable future scenarios showing how climate change will affect extreme hydrological and meteorological events.

The main aim of the present paper is to improve the existing knowledge about floods in medieval Poland based on documentary evidence. To fulfil this aim, a comprehensive database of floods was first constructed, based mainly on analysis of original historical sources. In addition, our research was supported by the use of existing compilations (e.g., Girguś and Strupczewski, 1965). In the next step, the quality of sources was estimated using critical source analysis and hermeneutics. Finally, the necessary basic statistical analyses were conducted to evaluate the frequencies, intensities, and origins of floods in Poland in the 11th to 15th centuries.

2. Study area, data, and methods

The study was carried for the area of present-day Poland and for its six most important geographical regions: Baltic Coast and Pomerania, Masuria-Podlasie, Greater Poland, Masovia, Silesia, and Lesser Poland (Fig. 1). However, the reader should be aware of the fact that the area of Poland changed quite often throughout the medieval times and only partly coincided with the present area of Poland. Therefore, it was necessary to use sources from provinces that did not belong to the Kingdom of Poland in the Middle Ages, such as Silesia, much of Pomerania and Masuria, and from neighboring countries to the extent that they were relevant.

In addition, in analyzing flood events, we focused primarily on Poland's main rivers, i.e. the Vistula and the Oder, and their basins. The analysis also covered all coastal rivers feeding into the Baltic Sea. When the historical sources contained no information about a geographical location (region), or only very general information, the flood was assigned to the category named "Poland".

The study area is located in Central Europe and mostly covered by two large river basins – those of the Vistula and the Oder (Fig. 1). The country borders the Baltic Sea to the north and the Carpathian Mountains to the south. The Vistula and Oder are among the five largest river basins in Central-Eastern Europe (Piniewski et al., 2017). The Vistula is the longest river (1024 km) in Poland and drains into the Baltic Sea. It flows from its sources in the north of Barania Góra in the Beskidy Mountains (Carpathian range), whereas the Oder River flows from the Oderské vrchy in the Sudetes (Cyberski et al., 2006; Piniewski et al., 2017). There are several cities in the Vistula basin, including Cracow, Warsaw, Płock, Włocławek, Toruń, Tczew, and Gdańsk (Cyberski et al.,

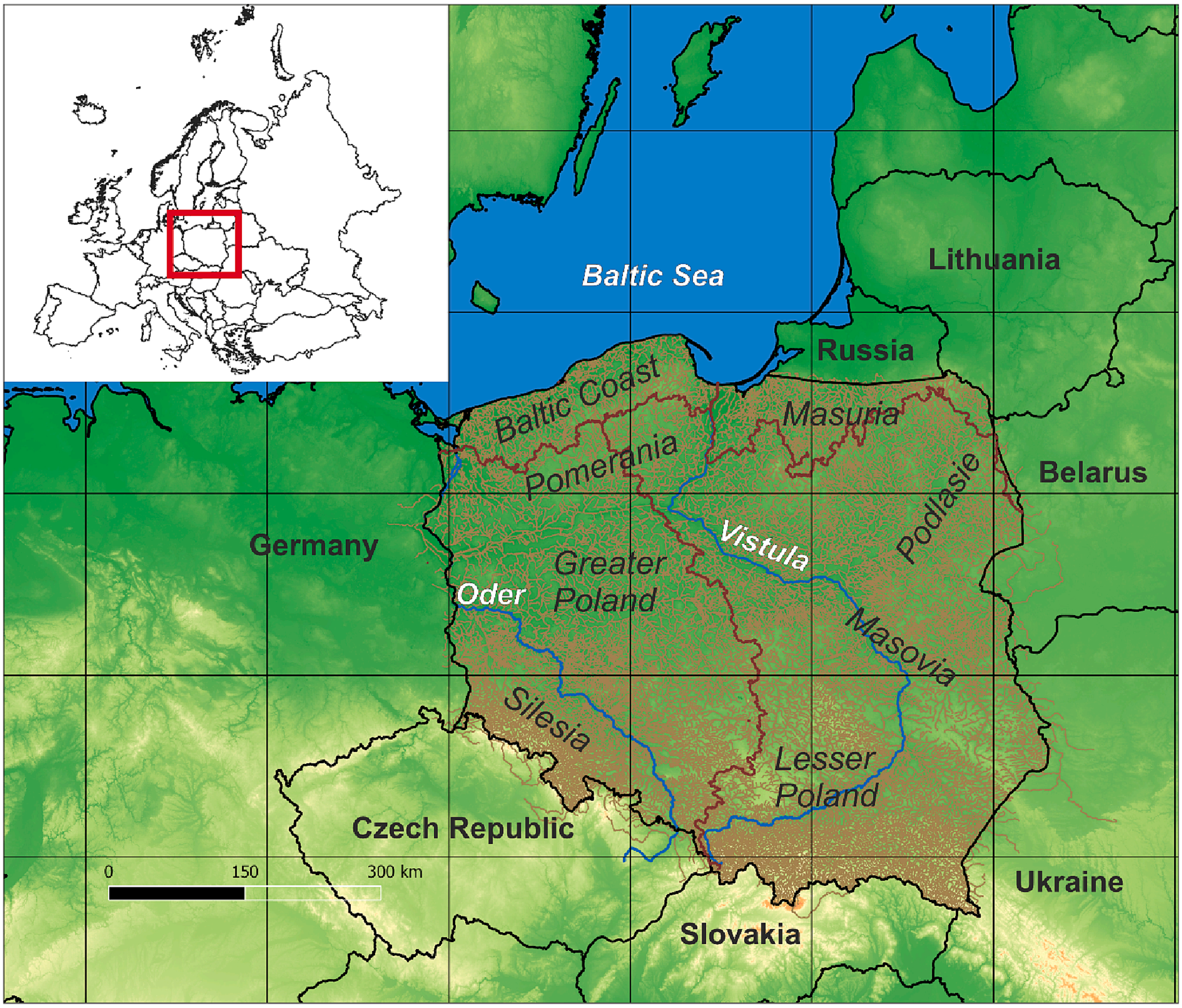

Fig. 1. Location of study area, including main rivers and geographical regions.

2006). In the Oder River basin, there are also Racibórz, Kędzierzyn-Koźle, Krapkowice, Opole, Brzeg, Oława, Wrocław and Szczecin.

In this research paper, a variety of documentary evidence was used to evaluate flood events in Poland, such as: narrative written sources (annals and chronicles); public administration documents; diaries; and private correspondence. The documentary evidence used for the inventory of floods was collected and recorded in Tables S1 snd S2 as well as in a comprehensive database of Nicolaus Copernicus University, Toruń (https://doi.org/10.18150/WD18XJ).

The methods applied in this research follow approaches to analyzing documentary evidence established and successfully used by various researchers (Jacobeit et al., 2003; Brázdil et al., 2006; Glaser et al., 2010) as briefly summarized by Glaser and Stangl (2004) in their Fig. 4. Key biases connected with the analysis of documentary evidence were also discussed in the above-mentioned publications and are therefore omitted here.

The results were elaborated in four main stages:

(1) the creation of a database of all flood events in Poland from the 11th to 15th centuries based on all available documentary evidence. The constructed database contains, besides a simple list of floods, important additional information such as: location, time and duration, original description, name of source, quality of sources (for more details see https://doi.org/10.18150/WD18XJ);
(2) a two-step indexation of flood categories using classifications proposed by Brázdil et al. (2006) and Barriendos and Coeur (2004) (for details see Tables 1 and 2). The first step of indexation involved all authors of the present paper referring to all sources containing information about the occurrence of floods in the study area from 11th to 15th centuries and each independently using the flood descriptions to perform a classification. For some floods, however, more than one source of data exists. Therefore, in the second step all such cases were carefully analyzed by the entire team and a final indexation was proposed taking particular account of the more reliable sources;
(3) the estimation of the origins of floods by the method propose by Lambor (1954) and modified by us (for details see Table 3);
(4) a basic statistical analysis of flood occurrence, including their intensity and origin.

The data elaboration procedure is presented in more detail in Fig. 2.

The capability of the methods proposed by Barriendos and Coeur (2004) and Brázdil et al. (2006) to classify and reconstruct the intensity of historical hydrological events has been approved in many recent studies (Camuffo et al., 2010; Glaser et al., 2010; Kjeldsen et al., 2014; Bhat et al., 2019; Blöschl et al., 2020; Alcoforado et al., 2021; Benito et al., 2021).

More detailed information about all floods is available in the electronic database we constructed (https://doi.org/10.18150/WD18XJ). The inventory is mainly a result of (i) analysis of old, existing databases

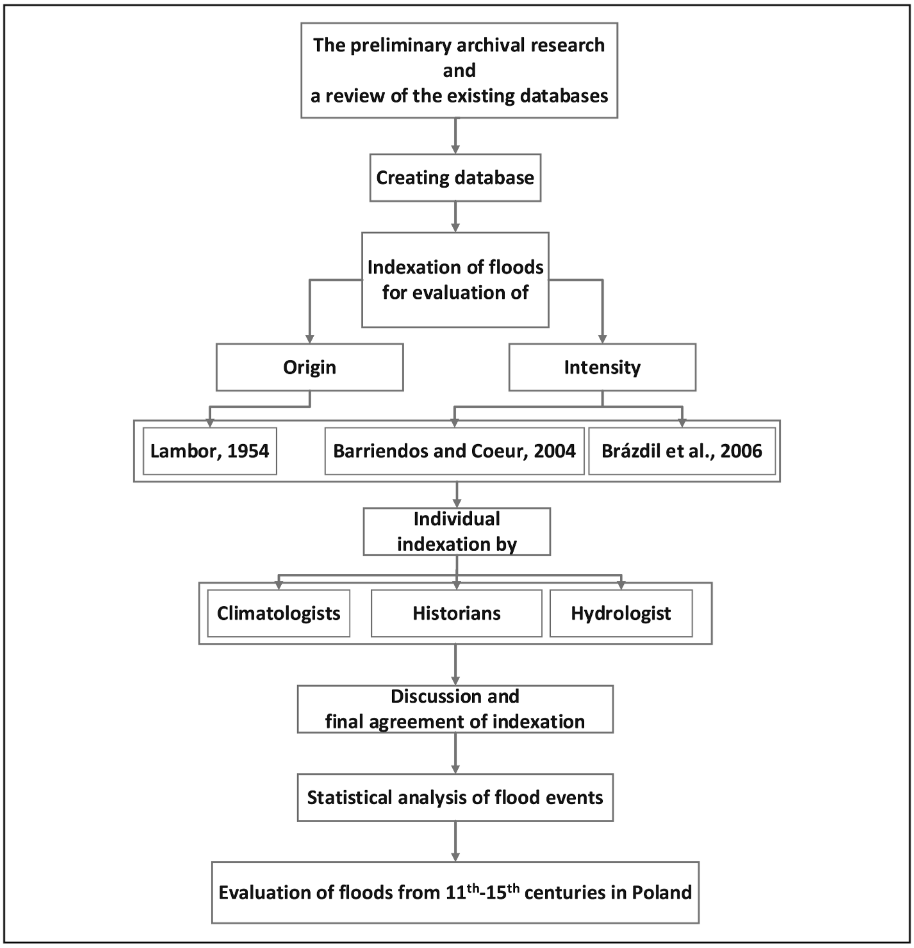

Fig. 2. Data elaboration procedure.

Table 1
Classification of floods based on intensity (source: Sturm et al., 2001; modified by Brázdil et al., 2006).

Index	Index classification	Description
0	flood	no additional reports
1	smaller, regional flood	little damage, e.g. riverside fields and gardens, wood supplies; short duration
2	above-average, or supra-regional flood	damage to water-related buildings and structures; average duration; severe damage to riverside fields and gardens; loss of animals, and sometimes human lives
3	above-average, or supra-regional flood on a disastrous scale	severe damage to water-related buildings and structures; some buildings completely destroyed or washed away; longer duration (days or weeks); severe damage to riverside fields and gardens; extensive loss of animals and human lives

containing weather descriptions we gathered in many previous projects, and (ii) newly undertaken preliminary archival research concentrating only on the occurrence of floods. For almost all identified floods, the original sources are given, together with an estimation of each source's quality using a three-degree scale: 1 – weak, 2 – moderate, and 3 – very good.

3. Results

In the paper we present an updated, quality-controlled inventory of

Table 2
Classification of floods based on intensity (Barriendos & Coeur, 2004).

Index	Index classification	Description
0	ordinary	in-bank flow; no damage; water discharge may increase but without overflowing
1	extraordinary	overflowing of river bed; damage but no destruction.; flood without destruction
2	catastrophic	overflowing of river bed; destruction of permanent infrastructure; flood with general damage and destruction.

Table 3
Classification of floods based on origin (Lambor, 1954, modified).

Index	Description
1	rain
(1a, 1b, 1c)	1a – torrential, 1b – frontal, 1c – long-lasting, territorially widespread
2	snowmelt
3	storm
4	winter
(4a, 4b)	4a – ice jam, 4b – shuga
5	Anthropogenic

Key: index "3″ here means floods noted in coastal parts of the Baltic Sea and large water bodies due to the occurrence of strong (gale) winds.

Table 4
Comparison of flood occurrences in Poland in 11th–15th centuries presented in this research and other literature sources.

Century	Current research*P	Grześ (2008)*P https://www.wielkawoda.umk.pl/czym_sa_znaki/prezentacja.pdf	Majewski (1993)*d	Bielański (1997)*u	Mudelsee et al. (2004)**	Kasprzak (2010)**
11th (2)	1097 (2)	1097		1097		
12th (7)	1118 (2), 1125 (2), 1151, 1152, 1179	1118, 1125, 1151, 1152, 1158??		1118, 1125		1158??, 1179
13th (15)	1219 (2), *1220* (2), 1221 (2), 1235 (2), 1253 (2), 1269, 1270 (2), 1281 (2)	1219, 1221, 1235, 1253, 1255??, 1269, 1270, 1281, 1299??		1221,1253, 1270, 1281	1269	1253, 1270, 1281
14th (40)	1304, 1310 (2), 1312 (2), 1316 (2), 1320, 1328, 1333?, 1337, 1342?, 1347, 1349?, 1350, 1351, 1359, *1360*, 1366, 1367, 1368, 1370, 1371, 1372, 1374, 1376, 1379, *1381*, 1385, 1387 (2), 1388 (3), 1393?, 1394, 1395, 1396, 1398, 1400,	1304, 1310, 1312, 1316, 1320, 1328, 1337, 1342, 1347, 1350, 1351, 1359, 1366, 1367, 1368, 1370, 1372,1374, 1376,1379, 1385, 1387, 1388, 1394, 1395, 1396, 1398, 1400	1328, 1329#1, 1337, 1338#2, 1371,1376, 1379, 1338#3, 1393, 1394, 1395	1312, 1359, 1376	1350, 1367,	1310, 1312, 1333, 1349, 1350, 1351, 1372, 1387, 1400
15th (102)	1403 (2), 1404, 1405, 1407, 1408, 1409, *1410*, 1412, 1413, 1414,1415 (2), 1416, 1417, 1421, 1426, 1427 (3), 1428 (2), 1430 (2), 1432, 1433, 1434 (2), 1437, 1440 (2), 1441, 1444, 1445, 1446, 1449, 1450, 1451 (3), 1452 (2), 1453, 1454 (2), 1455, 1456 (4), 1457, *1458*, 1459, 1460, 1461?, 1462 (2), 1463, 1464 (2), 1465 (2), 1466 (2), 1467 (3), 1468 (3), 1469, 1470 (2), 1472 (3), 1473, 1474 (2), 1475 (2), 1476, 1477 (2), 1479, 1480, 1481, 1482, 1486, 1488, 1491 (2), 1493 (2), 1495 (2), 1496 (2), 1497 (2), 1500 (2)	1403, 1404, 1405, 1407, 1408, 1409, 1412, 1413, 1414, 1415 (2), 1416, 1417, 1421, 1426, 1427, 1428, 1430, 1432, 1434, 1437, 1438??, 1440, 1441, 1444, 1445, 1446, 1449, 1451, 1452, 1453, 1454, 1455, 1456, 1457, 1459, 1462, 1463, 1464, 1465 (2), 1466 (2), 1467 (2), 1468 (2), 1470 (2), 1472, 1473, 1474, 1475, 1476, 1477, 1479, 1481, 1482, 1486, 1488, 1491, 1493, 1494#4, 1496, 1497, 1500	1403, 1407, 1408, 1409, 1415, 1416, 1421, 1427, 1428, 1430, 1434, 1440, 1446, 1450, 1452 1454, 1455 (2), 1456, 1461, 1462, 1463, 1464, 1465, 1466, 1470, 1472, 1474, 1476, 1479, 1481, 1482 (2), 1491 (2), 1497, 1500	1427 (2), 1451, 1468, 1470, 1475	1405, 1413, 1415, 1417, 1426, 1444, 1445, 1454, 1456 (2), 1464, 1468, 1470, 1472, 1495, 1496	1403, 1405, 1412, 1415, 1417, 1427, 1428, 1432, 1433, 1434, 1440, 1441, 1444, 1445, 1451, 1452, 1453, 1454, 1456, 1460, 1462, 1464, 1468, 1469, 1470, 1472, 1475, 1480, 1493, 1495, 1496, 1500

Explanations:
*P – floods for entire Poland; *d – floods for Vistula River Delta only; *u – floods for Upper Vistula River only; ** – floods for Oder River Basin only.
() – more than one flood in the year is given.
Column 1 – the number (in parentheses) of floods per century as identified in the present research.
italic font – new floods not present in any other listed source.
? – probable flood, these cases were included in our database and statistical analysis.
Characters added by the authors of this publication and their explanations:
?? – not probable flood; no available source or wrong interpretation of source information.
#1 – the cited item (Toeppen 1894) contains no information about a flood.
#2 – the cited item (Toeppen 1894) contains no information about a flood in this year; should probably be 1388 (i.e., probable typographical error).
#3 – erroneous year, should be 1388 (i.e., probable typographical error).
##4 – erroneous year based on information about tax exemptions after a flood in the previous year.
All these floods listed by Grześ (2008) or Majewski (1993) were excluded from our database and statistical analysis.

historical floods in Poland from the 11th to 15th centuries that is currently the most complete such inventory (Table S1, Table 4). We also checked the reliability of all available lists of floods in Poland published in the Polish literature, which were usually not constructed in close co-operation with historians. Some dates of flood occurrences in that literature have insufficient evidence in reliable sources to fully accept the correctness of the given dates. For some floods included in these previous lists, no source is even provided. For all those cases, we searched all known databases and historical sources to obtain Supporting information on the occurrence of floods in these years. The probability of their occurrence was estimated and is indicated in Table 4.

Analysis of all the mentioned documentation revealed 166 floods in the study period. The greatest numbers (102, i.e. 61.4%) were noted in the 15th century and 14th century (40, 24.1%) (Fig. 3). Before the 14th century, recorded floods were very few, numbering only 24 (14.5%). The main reason for this fact is the growing number of available historical sources, in particular since the 14th century. For the first three centuries we gathered only 15 sources, while for the 14th and 15th centuries 149 sources. However, other important reasons for floods in Poland being most frequently reported in this time are the observed increase in number of settlements and increased deforestation near rivers (Starkel, 2001). From the mid-14th century, the construction of the first, but poorly-built, dikes in the Lower Vistula paradoxically also caused an increase in the number of floods (Cyberski et al., 2006). The reason was the increase in population density in the river valley behind the dikes due to the false sense of security. In reality, however, they were easily and often broken by waters.

The spatial diversity of flood occurrences in Poland was characterized for river basins (Vistula, Oder and Baltic Coast) and for geographical regions (Table S3, Fig. 4). Floods were registered most often for the Vistula River basin, where 84 cases were noted. A significantly smaller number of floods (69) was observed in the Oder River basin. However, floods were most rarely noted (only 13) in the basin of the Baltic Coast rivers.

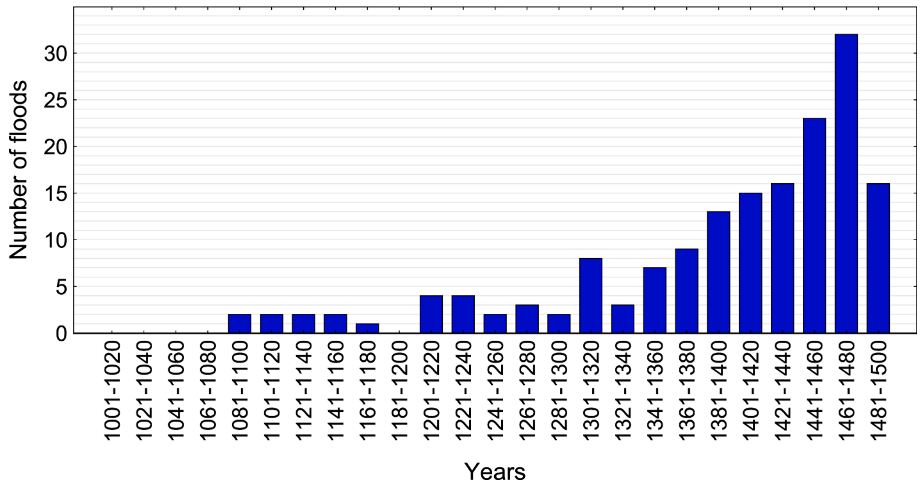

Fig. 3. Numbers of floods in 20-year periods in Poland from 1001 to 1500.

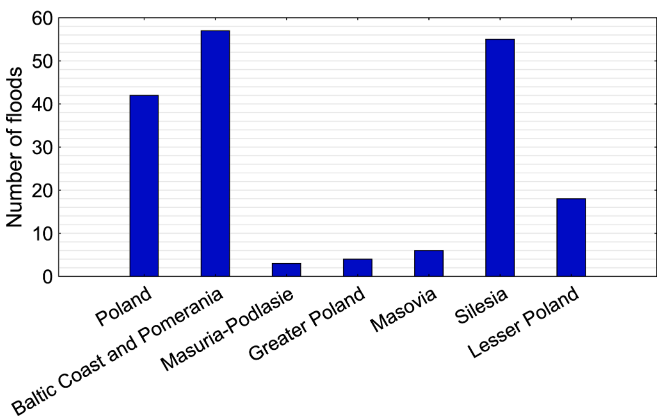

Fig. 4. Number of floods in various geographical regions of Poland during 11th–15th centuries.

Analysis of the floods occurrences in different geographical regions (Fig. 4) reveals significant spatial differentiations. The majority of floods in Poland during the 11th–15th centuries occurred in the Baltic Coast and Pomerania region and Silesia region. In the first region, the number of floods was the greatest and reached 57 (34.3%). Slightly fewer floods (55, 33.1%) occurred in the Silesia region. In none of the other regions does their frequency in the study period exceed 20 cases. Of those regions, they were most commonly observed in Lesser Poland (18, 10.8%) (Fig. 4). The available weather notes did not always precisely describe the area of the flood occurrences. Such cases (42, 25.3%) were attributed to the another category called "Poland".

Table S3 and Fig. 5 presents the results of the indexation of flood intensities and origins in Poland based on the classifications of Brázdil et al. (2006), Barriendos and Coeur (2004) and Lambor (1954) (for details, see Tables 1–3).

According to the Brázdil et al. (2006) classification, the "above average or supra-regional floods" category was most common (77 cases) in Poland in the period 1001–1500. The other distinguished flood categories were less than half as common (Fig. 5a). The flood events indexation according to the classification of Barriendos and Coeur (2004) shows that category of "extraordinary" floods (1) occurred more often (99 cases, 59.6%) than other distinguished flood categories. The category of "catastrophic" floods was also quite common (62 cases, Fig. 5b), while the category "ordinary" was rare.

Another very important research issue we undertook was to estimate

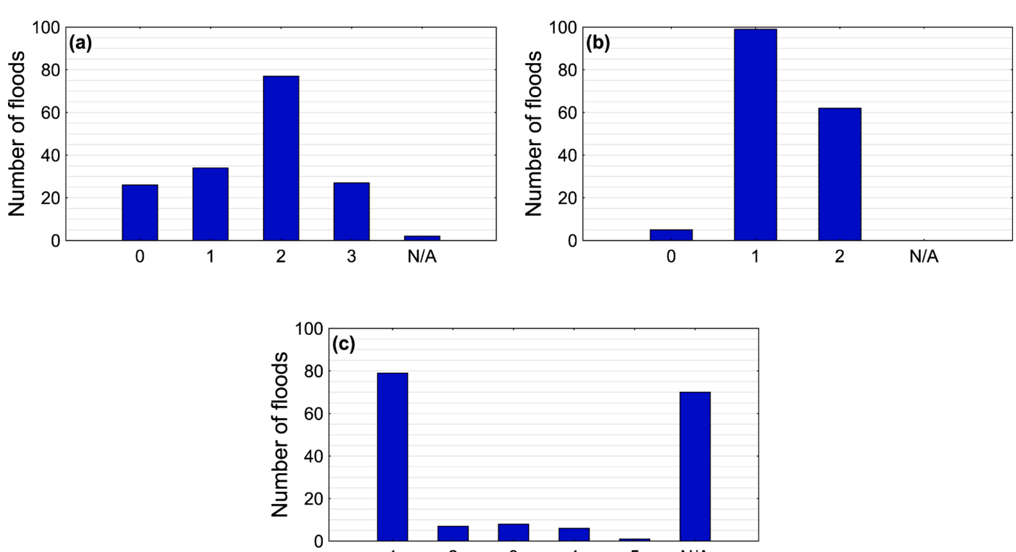

Fig. 5. Total number of different categories of flood intensities in Poland in the period 1001–1500 based on classifications of (a) Brázdil et al. (2006) and (b) Barriendos and Coeur (2004); and (c) categories of origin of floods based on Lambor (1954). Key: N/A means information is not available.

the origin of each flood. However, this task was very often not easy, because the descriptions available for the floods are sometimes very modest. This was true of 70 floods (42.2%). The decidedly greatest reason for floods in Poland in the 11th–15th centuries was rain – more specifically, three sub-types thereof (see Fig. 5c). For 79 flood events (47.6%) we were able to find evidence for this. For slightly more than half of them (45 cases) it was also possible to indicate the subtype according to the classification of Lambor (1954). Categories 1a (torrential rain) and 1c (long-lasting, territorially widespread rains) were the most common reason for floods (respectively, 16 and 27 events). For only two floods did we find strong evidence that the reason was frontal rain (category 1b). The number of floods attributed to the remainder of categories proposed by Lambor (1954), i.e. to snowmelt (category 2), storm (3), and winter (4) were very small, at only 7, 8, and 6, respectively.

The Polish literature very often mentions or lists only extreme or major floods. For this reason, we used our database also to distinguish such floods. Here, we assumed "extreme floods" that occurred in Poland in the 11th to 15th centuries to be all floods that we indexed as category 3 (after the classification of Brázdil et al. 2006) or category 2 (after Barriendos and Coeur, 2004). We found 49 such cases, and all of them are listed in Table 5. The flood category 3 proposed by Brázdil et al. (2006) is evidently stricter (only 20 extreme floods), whereas the criterion for flood category 2 based on the classification of Barriendos and Coeur (2004) reveals existence of 49 extreme floods.

4. Discussion

Although the Polish literature has different sources for historical meteorological and hydrological events, there are only a few studies that investigate the occurrence of flood events in Poland during the 11th–15th centuries. To evaluate the correlation of these results with other studies in Poland and other parts of Europe – especially central Europe – we compared our results with previous studies (see Tables 4–6). This is the first time that an inventory of floods for all of Poland in the 11th–15th centuries has been published that lists not only years of flood occurrences but also complete information about sources (including weather notes) and source quality, as well as estimations of the intensity and origin of almost every flood. For the area of Poland, we only found one unpublished item by Grześ (2008) listing years of floods (see Table 4), but without any additional information. Therefore, it is difficult to check the reliability of the occurrence of some floods, as they are not confirmed by sources and are not contained in our database. Generally, however, our inventory of floods made independently for this paper shows good agreement with the list of flood occurrences presented by Grześ (2008). In the published literature we found only a few inventories of floods (Table 4) that occurred in the Vistula delta (Majewski, 1993), the upper Vistula (Bielański, 1997), and the Oder basin or some parts thereof (Mudelsee et al., 2003; Kasprzak, 2010). All of these inventories were prepared mainly based only on information available in works published in recent decades. Nevertheless, the mentioned inventories or catalogues of floods were found to correlate well with our database (Table 4). There are also flood statistics (but not a list of individual floods) for 10-year periods calculated by Pawłowski (2003). A figure presenting these statistics in modified form (i.e., showing frequency for 20-year periods) was also published in the review paper written by Cyberski et al. (2006).

The number of floods in Central Europe in medieval times is presented in Table 6 and Fig. 6. The comparison of results is not simple due to biases mainly related to differences in the degree of availability or completeness of documentary evidence between countries. Some are also probably related to the spatial coverages of flood inventories. For example, flood inventories cover Hungary and Poland in their entirety, but only some river basins of Czech Republic and Germany (see Table 6). Therefore, to reduce the influence of some biases, we present only the relative frequencies of floods having occurred simultaneously in Poland and in one of the three analyzed countries. Analysis shows that about 63% and 60% of floods that occurred in the Czech Republic and in Germany, respectively, were also noted in Poland. With Hungary, this agreement was slightly smaller and reached 49% of cases. In the eleven years of 1316, 1342, 1367, 1432, 1433, 1434, 1437, 1445, 1481, 1491, and 1496, the floods occurred across all the studied countries of Central Europe.

In historical times and at present, the greatest attention has been directed at extreme and catastrophic floods throughout history that caused the greatest losses in human lives and to economic and cultural infrastructure. Therefore, we also compared the occurrence of such floods in Poland and neighboring countries (Table 5). Again, the comparison is not easy because, in addition to the biases described earlier, there is one more difficulty associated with the differences in criteria used to delimit categories of extreme floods. In the Polish literature, except in this study, those criteria are generally not even given (see, e.g., Kowalewski, 2006; Kubiak-Wójcicka, 2014). It is also difficult to find a complete list of floods for longer periods, and often only some (or even only individual cases) are mentioned and described.

The only list of years in which extreme floods occurred in Poland in the 11th–15th centuries was given by Kowalewski (2006) based on information available in Polish publications from the 1990s. For the study period, he found 21 major floods, while we identified 49 such floods according to the two sets of criteria we used (see Table 5). A significant proportion of the floods (33.3%) mentioned by Kowalewski (2006) is also present in our database. The best correspondences between the above-mentioned inventories of floods were found for the 13th century (40%) and the 15th century (50%). Kubiak-Wójcicka (2014) reported that at least five extreme floods occurred in Toruń (Vistula River) during

Table 5
Comparison of extreme floods in Poland, Germany and Czech Republic, 11th–15th centuries.

Century	Poland* (this research)	Poland (Kowalewski, 2006)	Germany *Oder River* Elbe River (Mudelsee et al., 2003)	Czech Republic Prague Vltava River (Elleder, 2015)
11th		1097		
12th		1118		1118, 1141
13th	*1219*, *1253*, **1270**	1221, 1235, 1253, 1270, 1299		1257, 1272, 1273, 1281
14th	**1304**, **1310**, **1316**, **1320**, *1337*, *1351*, *1370*, **1372,** *1374*, *1376*, *1385*, *1387*, *1388*, **1393**, *1396*	1310, 1342, 1347, 1368	1315, 1316, 1342	1315, 1316, 1321, 1342, 1359, 1364, 1367, 1370, 1373, 1374, 1387, 1392
15th	*1403*, *1405*, *1410*, *1415*, *1426*, *1427*, *1428*, **1432**, **1433**, **1434**, **1445**, **1449**, *1450*, *1456*, **1460**, **1462**, **1464**, **1465**, **1466**, **1467**, *1468*, *1470*, *1475*, *1476*, *1477*, *1488*, *1491*, *1493*, *1496*, **1497**, **1500**	1404, 1414, 1438, 1451, 1456, 1459, 1468, 1475, 1493, 1500	1434, *1496*	1432, 1445, 1481

*Normal font for flood category 3 (Above-average, or supra-regional flood on a disastrous scale) based on Brázdil et al. (2006) classification; *Italic* font for flood category 2 (catastrophic) based on Barriendos and Coeur (2004) classification; and **bold** font for years that are common to both of classifications.

Table 6
Comparison of flood occurrences in Poland and some Central European countries, 11th–15th centuries.

Century	Current research (Poland)	Mudelsee et al. (2003) (Germany) Elbe	Brázdil et al. (2005) (Czech Republic) Vltava, **Ohře**, *Elbe*	Kiss (2019) (Hungary)
11th	1097(2)	1059		1051
12th	1118(2), 1125 (2), 1151, 1152, 1179	1118, 1141, 1163	1118, *1118*, 1121/22, 1126, *1126*, 1141	1147, 1154
13th	1219 (2), 1220 (2), 1221 (2), 1235 (2), 1253 (2), 1269, 1270 (2), 1281 (2)	1275	1250, *1257*, 1257, 1264, *1264*, 1270, 1272, 1273, 1281	1229, 1235, 1245, 1260, 1267, 1268 (2), 1270, 1285, 1294, 1296, 1300
14th	1304, 1310 (2), 1312 (2), 1316 (2), 1320, 1328, 1333?, 1337, 1342?, 1347, 1349?, 1350, 1351, 1359, *1360*, 1366, 1367, 1368, 1370, 1371, 1372, 1374, 1376, 1379, *1381*, 1385, 1387 (2), 1388 (3), 1393?, 1394, 1395, 1396, 1398, 1400,	1306, 1315, 1316, 1342 (2), 1343, 1367, 1400	*1315*, 1315, 1316, *1316*, 1321, *1321*, 1327, 1342, *1342*, 1359, **1359**, *1359*, 1364, 1367, *1367*, 1370, *1370*, 1373, 1374, **1374**, 1387, 1392, *1392*	1316, 1325, 1328, 1334, 1333(2), 1335 (2), 1338 (2), 1341 (2), 1342 (3), 1343 (3), 1344 (2), 1345, 1346, 1347, 1348, 1349 (2), 1355, 1357 (2), 1358, 1359, 1362, 1363, 1364, 1366 (2), 1367 (2), 1372, 1373, 1374, 1377 (2), 1378, 1382, 1383, 1389, 1393, 1396 (3), 1399 (3), 1400
15th	1403 (2), 1404, 1405, 1407, 1408, 1409, *1410*, 1412, 1413, 1414,1415 (2), 1416, 1417, 1421, 1426, 1427(3), 1428 (2), 1430 (2), 1432, 1433, 1434 (2), 1437, 1440 (2), 1441, 1444, 1445, 1446, 1449, 1450, 1451 (3), 1452 (2), 1453, 1454 (2), 1455, 1456 (4), 1457, *1458*, 1459, 1460, 1461?, 1462 (2), 1463, 1464 (2), 1465 (2), 1466 (2), 1467 (3), 1468 (3), 1469, 1470 (2), 1472 (3), 1473, 1474 (2), 1475 (2), 1476, 1477 (2), 1479, 1480, 1481, 1482, 1486, 1488, 1491 (2), 1493 (2), 1495 (2), 1496 (2), 1497 (2), 1500 (2)	1404, 1413, 1422, 1428 (2), 1431, 1432 (2), 1433 (2), 1434, 1435, 1437, 1443, 1445, 1446, 1449, 1451, 1457, 1480, 1481, 1488, 1491, 1493, 1495, 1496, 1497, 1498 (2)	1405, *1405*, 1432 (3), **1432**, *1432 (2)*, 1433, *1433*, 1434, *1434*, *1437*, 1445, *1445*, *1454*, **1457**, **1459**, **1461**, 1464, **1464**, *1464*, 1481, 1491, *1491*, 1496, *1496*	1400, 1402 (3), 1405, 1406, 1408, 1409, 1410, 1411, 1412, 1413 (2), 1414, 1416, 1417, 1419, 1421 (2), 1422 (2), 1423, 1424 (3), 1426 (2), 1432 (2), 1433, 1434, 1435, 1436 (2), 1437 (2), 1439 (2), 1440 (2), 1442, 1443 (2), 1444 (2), 1445, 1446, 1447, 1454 (3), 1458 (2), 1465, 1466 (2), 1468, 1469 (2), 1472, 1476, 1478 (2), 1480 (2), 1481, 1482, 1484, 1485 (2), 1486, 1487, 1488, 1489, 1490, 1491 (2), 1493 (2), 1495 (2), 1496 (2), 1498, 1499 (3), 1500

Key: number of floods in a year is given in brackets, if greater than 1;? – probable flood; *italic* – floods in Elbe River; **bold** – floods in Ohře River.

the 14th and 15th centuries (1312, 1331, 1366, 1465/66, and 1493). Only the last two of these were confirm as extreme floods by us in our database, whereas the others were categorized as normal (1312 and 1366) and no flood in 1331 is present in any database for Poland presented in Table 4.

Elleder (2015) identified 21 extreme floods for the River Vltava at the Prague profile. He used a discharge of around Q_{10} as a threshold for denoting real extreme flood events. Only six of these (28.6%) also occurred at the same time in Poland, but all of those in the 14th and 15th centuries did. The most probable reason for this is the documentary evidence for these two countries being more precise and reliable for the 14th and 15th centuries than for earlier centuries. In their catalogues of floods for the Oder and Elbe rivers, Mudelsee et al. (2003) also distinguished three categories of flood intensities using criteria proposed by Brázdil et al. (1999). The criteria for extreme floods (category 3) are the same as we used in the present paper after Brázdil et al. (2006). For the study period, Mudelsee et al. (2003) identified only four exceptionally strong flood events out of all 42 floods identified for the Elbe River (1315, 1316, 1342, and 1434), and only one out of 19 for the Oder River (1496) (see Table 5). It seems that the number of that category of floods is so small in comparison with neighboring countries (i.e., Czech Republic and Poland) (Table 5) mainly due to the incompleteness of Weikinn's catalogue of medieval floods (see listing all floods in Table 6) that Mudelsee et al. (2003) used as the main source of flood records for the Elbe and Oder rivers. Mudelsee et al. (2003) were aware of this fact, writing that "records may not be homogeneous before ~1500". Though not the 1315 flood on the Elbe River, the three others listed in Table 5 were estimated as extreme events also in Poland. In the case of the Oder, the 1496 flood was qualified as extreme only in Poland, and not in the Czech Republic or Hungary.

In studying the nature of floods, it is very important to recognize their origins. However, such information is limited in the documentary evidence for the study period. For example, Elleder (2015) and Kiss (2019) were only able to find information sufficient to estimate the origin of floods in the Czech Republic and Hungary for only 9.5% and 19.7% of cases, respectively. Better results were obtained by Mudelsee et al. (2003); they were able to estimate the origin of 33.3% and 42.10% of floods for the Elbe and Oder rivers, respectively. The documentary evidence in our database allowed the origin of floods in Poland in the study period to be estimated in as many as 57.8% of cases.

Pawłowski (2003) estimated the reasons for floods according to just two categories: non ice-jam floods and ice-jam floods. This approach allowed the origin of all floods to be estimated, as Fig. 6 in his PhD work (p. 34) shows. Almost all of the 64 cases he distinguished (except four) were classified as "non ice-jam". However, in light of our results based on a detailed study of all available original historical sources, the indexation made by Pawłowski (2003) suffers from the questionable reliability of sources and a lack of information on some of the floods.

The results show that reconstructing flood occurrences in medieval times in Poland (as in any other country or region, of course) is a very difficult and time-consuming task. Obtaining more objective results based on subjective historical sources requires close cooperation between historians, climatologists, and hydrologists, especially when

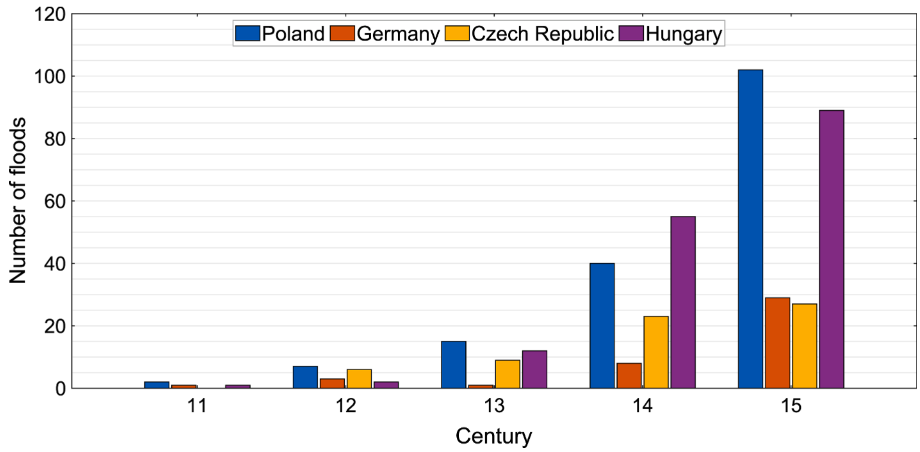

Fig. 6. Number of floods in Poland, Germany, Czech Republic and Hungary, 1001–1500.

estimating the intensity and origin of each flood. Our study reveals the good capacity of documentary evidence to provide valuable information for evaluating historical floods in Poland, as many other studies cited herein have stated for other European regions. The present study has filled the knowledge gap regarding historical flood occurrences in Poland from the 11th to 15th centuries. In addition, these historical flood records can provide helpful information to hydrological analysis and estimation of flood return periods and can be consulted in designing various hydrological infrastructures. It is expected that the results of this study will also help researchers and hydrologists in preparing quantitative works. There are various examples for quantitative flood modeling, flood hazard assessment, and flood frequency analysis based on historical evidence (Engeland et al. 2018; Ngo et al. 2023; Benito et al. 2021). Finally, the results should be a helpful source of information for improving knowledge of flood occurrences in Europe, particularly in Central Europe.

5. Conclusions and final remarks

A comprehensive study of the flood occurrences in Poland in medieval times (from the 11th to 15th centuries) based on available documentary evidence confirmed that such sources provide very valuable information about many aspects of floods, including, in addition to frequency, the possibility of estimating their intensities and origins. Besides the quality control of all available historical sources, which was carefully done by a team of historians, a reliable analysis of flood characteristics (e.g., an indexation of intensities and an estimation of origins) needs close cooperation between historians, climatologists, and hydrologists. The inventory of floods in Poland from the 11th to 15th centuries constructed for the paper is at present the most comprehensive and reliable source of information available for the study area and time. Furthermore, the inventory includes not only the dates of floods, as is typical of most previous publications, but also all available sources for each flood with an indication of the most reliable one. The description of the flood from the most reliable source is also given (Table S1, see also database: https://doi.org/10.18150/WD18XJ).

The main results of the present paper can be summarized as follows:

1. A total of 166 floods were recorded in the study period. The greatest number (102, i.e. 61.4%) was noted in the 15th century, and the second greatest in the 14th century (40, 24.1%) (Table 4, Fig. 3). Before the 14th century, recorded floods were very few (24, 14.5%), mainly due to the limited number of available sources. For example, for this period we collected only 15 sources, while for the last two centuries of the study period 149 sources.
2. Floods were registered most often for the Vistula River basin (84 cases). Significantly fewer floods (69) were observed in the Oder River basin. There were significant spatial differentiations in flood occurrence between geographical regions (Fig. 4). The most 11th–15th-century floods occurred in Baltic Coast and Pomerania (57, 34.3%) and in Silesia (55, 33.1%).
3. The "above average or supra-regional floods" category was most common (77 cases) in Poland in the period 1001–1500 according to the classification of Brázdil et al. (2006) (Fig. 5a). The flood events indexation according to the Barriendos and Coeur (2004) classification shows that "extraordinary" floods (category 1) occurred more often (99 cases) than other distinguished flood categories. The "catastrophic" floods category was also quite common (62 cases, Fig. 5b). This statistic confirms the opinion of Glaser and Strangl (2004) that medieval historical sources mainly described major anomalies and natural disasters.
4. The main reason for floods in Poland in the 11th–15th centuries was the three sub-types of rain (47.6%, 79 cases) (see Fig. 5c). Categories 1a (torrential rain) and 1c (long-lasting, territorially widespread rains) were most common (respectively, 16 and 27 cases). Reasons for floods that are indeterminate (42.2% of cases) due to a lack of appropriate information can bias this evaluation, but we see no cause to suppose that this effect should be significant.
5. Good spatial coherency of flood occurrences in Poland was found with neighboring countries. Analysis shows that about 63% and 60% of floods that occurred in the Czech Republic and Germany, respectively, were also noted in the area of Poland. (Table 6). The greater the distance from Poland, the lower the correlation between flood occurrences. For Hungary, the agreement fell to 49%. However, in some years (1316, 1342, 1367, 1432, 1433, 1434, 1437, 1445, 1481, 1491, 1496), floods occurred across all the Central Europe countries examined.
6. Surprisingly, a markedly smaller spatial correlation was found for the extreme floods category than for all floods (Table 5). It seems that this phenomenon is caused mainly by large biases related to differences in the criteria used to defined extreme floods. The quality and detail of the historical sources are also important in classifying floods.

The present study put in order and updates the list of floods in medieval times on the territory of present-day Poland and should therefore be helpful in improving knowledge of flood occurrences in Europe, and particularly in Central Europe. The output of this study may also be interesting and valuable to researchers and policymakers concerned with climate change and its impact on hydrometeorological events such as floods.

The present paper is the first in a series that we plan to publish in the near future. The next paper will present all flood characteristics analyzed here for Poland in the 16th–18th centuries.

CRediT authorship contribution statement

Babak Ghazi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Rajmund Przybylak:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Funding acquisition, Project administration, Validation, Supervision, Writing – original draft, Writing – review & editing. **Piotr Oliński:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation. **Katarzyna Bogdańska:** Methodology, Investigation, Data curation. **Aleksandra Pospieszyńska:** Methodology, Investigation, Data curation, Formal analysis, Validation, Software, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Data Availability Statement

The dataset of flood records for Poland during the 11th–15th centuries is available at (https://doi.org/10.18150/WD18XJ). Other data used in this research are available from the corresponding author, upon reasonable request.

Significance statement:

Floods are very dangerous natural disasters that affect all aspects of life, including agriculture, industry, education, and humans. It is well-established that human activity is the primary driving mechanism of the recent great warming in the world. Floods are expected to be more frequent and more dangerous in the world, including in Poland (Kundzewicz and Matczak, 2012). A long-term perspective on their occurrence and nature is crucial for each region. The present paper analyses in detail the occurrence of floods in Poland in medieval times. The study used the most comprehensive and reliable inventory of floods in Poland from the 11th to 15th centuries based on documentary evidence. Results should be helpful in improving the knowledge of floods in Europe, particularly in Central Europe.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2023.129778.

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An assessment of flood occurrences in Poland in the 16th century

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ABSTRACT

Study region: The contemporary area of Poland comprises six main regions: Baltic Coast and Pomerania, Masuria-Podlasie, Greater Poland, Masovia, Silesia, Lesser Poland, and three main river basins, the Vistula, the Oder, and the Baltic Coast.
Study focus: To fill the knowledge gap for historical floods in Poland we used documentary evidence as reliable sources to assess historical floods in Poland during the 16th century.
New hydrological insights for the region: This research is one of the most novel and comprehensive studies of historical floods in Europe, spanning floods in Poland registered in the 16th century. Specifically, in addition to the list of flood occurrence records, we also provide detailed information about the historical sources used (including estimations of credibility), extracted weather notes, and indexation of flood intensity and origins. The results showed that, based on documentary evidence, 294 floods occurred in Poland in the study period. Most were recorded in the Silesia region (170 floods). The intensity of floods estimated based on the Brázdil et al. (2006b) and Barriendos and Coeur (2004) classifications indicated that most belong to "above-average or supra-regional flood" and "extraordinary" categories, respectively. Classifications of the origin of floods based on Lambor (1954) revealed that the main reason for flood occurrences in Poland during the 16th century was rain and its subtypes (torrential, frontal, and long-lasting, accounting for 53% of floods).

1. Introduction

In light of current and projected global warming, the assessment of extreme hydrological and climatic events has great importance. For example, it is expected that the high frequency and intensity of floods observed in recent decades will increase even more in future decades almost everywhere across the globe (IPCC, 2021). Being among the most hazardous of natural disasters, floods still continue globally to affect human lives, economies, ecosystems and the environment. Floods are the greatest contributing factor in tens of thousands of deaths and various public health issues, as well as being the greatest single cause of economic losses among natural disasters. The average global loss due to floods is estimated at US$ 104 billion annually, and it is expected to increase by the end of the century with urbanization, economic growth and climatic change (Desai et al., 2015; Winsemius et al., 2016; Blöschl et al., 2019). In the last decades, in Europe, many climate-change-induced floods have caused immense social and economic damage (Blöschl et al., 2017). Therefore, the evaluation of such extreme hydrological events is essential.

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Knowledge of past hydrological events (i.e., floods and droughts) can provide valuable information to assess the future of extreme hydrological and climatological phenomena. Accessing historical instrumental measurements in previous centuries, particularly from before the 19th century, is challenging due to the very limited availability of such datasets. In that case, historical hydrology can provide reliable information regarding past hydrological events. In basic terms, historical hydrology is the interdisciplinary research interface between history and hydrology. The main aims of historical hydrology can be defined as reconstructing the spatial and temporal resolution of extreme events (i.e., floods, droughts), mainly in the period before hydrological networks were established. Additionally, historical hydrology can provide detailed information about the past impact of extreme hydrological events on human societies and the environment (Brázdil et al., 2006b). In this interdisciplinary subject, researchers use various proxy data to reconstruct this past extreme phenomenon. Our previous studies (Przybylak et al., 2005, 2020, 2023; Ghazi et al., 2023) showed that the documentary evidence available for Poland is a reliable proxy source that is important for the evaluation of past extreme hydrological and climatic events. Therefore, in this research we also used this kind of proxy data to assess floods in Poland in the 16th century.

In recent years, researchers have evaluated historical flood events in various parts of Europe (Mudelsee et al., 2003, 2004; Marchi et al., 2010; Blöschl et al., 2019; Benito et al., 2021). However, despite various attempts to fill the knowledge gap for historical floods, most of these studies cover mostly flood events for the 18th century and later (Mudelsee et al., 2003, 2004; Brázdil et al., 2006a; Cyberski et al., 2006; Cœur and Lang, 2008; Tarasova et al., 2019). In Poland, most studies cover mainly the last 200 years and are published in Polish (for a review, see Ghazi et al., 2023). For this reason, they are poorly known in the international research community. Additionally, most previous studies (especially those analyzing historical floods, i.e., before the instrumental period of observations) rarely investigated the intensity and origin of floods. Therefore, to fill the knowledge gap for the reconstruction of extreme hydrological events before the 19th century, we first created a comprehensive database of all historical floods in Poland during the 11th–15th centuries based on documentary evidence. This database was then used to evaluate the frequency, intensity and origin of floods in Poland in that period (Ghazi et al., 2023). However, there is still a knowledge gap for flood events during the 16th–18th centuries in Poland. In the present paper, we limited the study to the 16th century because this century was exceptional in Central Europe, including Poland, in terms of the large number and extremely high intensity of floods. Based on documentary evidence, in the 16th century, several extreme floods caused catastrophic damage in Central Europe, including Poland (Brázdil et al., 1999; Rohr, 2007; Kiss and Laszlovszky, 2013). In addition, various sources confirm that the number of floods was greater in the 16th century than in other centuries in some parts of Europe. For example, Grześ (2008) mentioned 89 flood occurrences in Poland in the 16th century, which is more than the 67, 30 and 40 floods in the 15th, 17th and 18th centuries, respectively. Similar results were presented by Mudelsee et al. (2003); they reported 70 and 38 floods for

Fig. 1. Geographical location of the study area.

the Elbe and Oder rivers in the 16th century alone, while their numbers for the entire medieval period (11th–15th centuries) totaled only 42 (Elbe) and 19 (Oder). Blöschl et al. (2020) distinguished and compared flood-rich periods for several European countries in the past 500 years. The authors concluded that 16th century Central Europe was one of the most flood-rich locations in Europe's history. Benito et al. (2003) evaluated the number of floods in the Tagus basin (Central Spain) in the last millennium and concluded that the frequency of floods during the period 1540–1640 (11%) was significantly greater than (more than two times) that of other periods of high flood numbers: 1160–1210 (3%), 1730–1760 (5%), and 1780–1810 (4%).

For the above-mentioned reasons, the main objective of this research is to provide a comprehensive assessment of all historical floods in Poland during the 16th century based on documentary evidence. The results of this study will extend current knowledge based on instrumental and historical data. In addition, flood risk estimation is important for civil and hydraulic engineers when designing and operating hydraulic structures (e.g., dams, weirs) (Stamataki and Kjeldsen, 2021). In the designing of these structures, to cope with a flood, it is very important to consider a pre-defined return period (Stamataki and Kjeldsen, 2021). Therefore, extending the period for which reconstructions of historical floods exist can contribute to better understanding for designing such infrastructures.

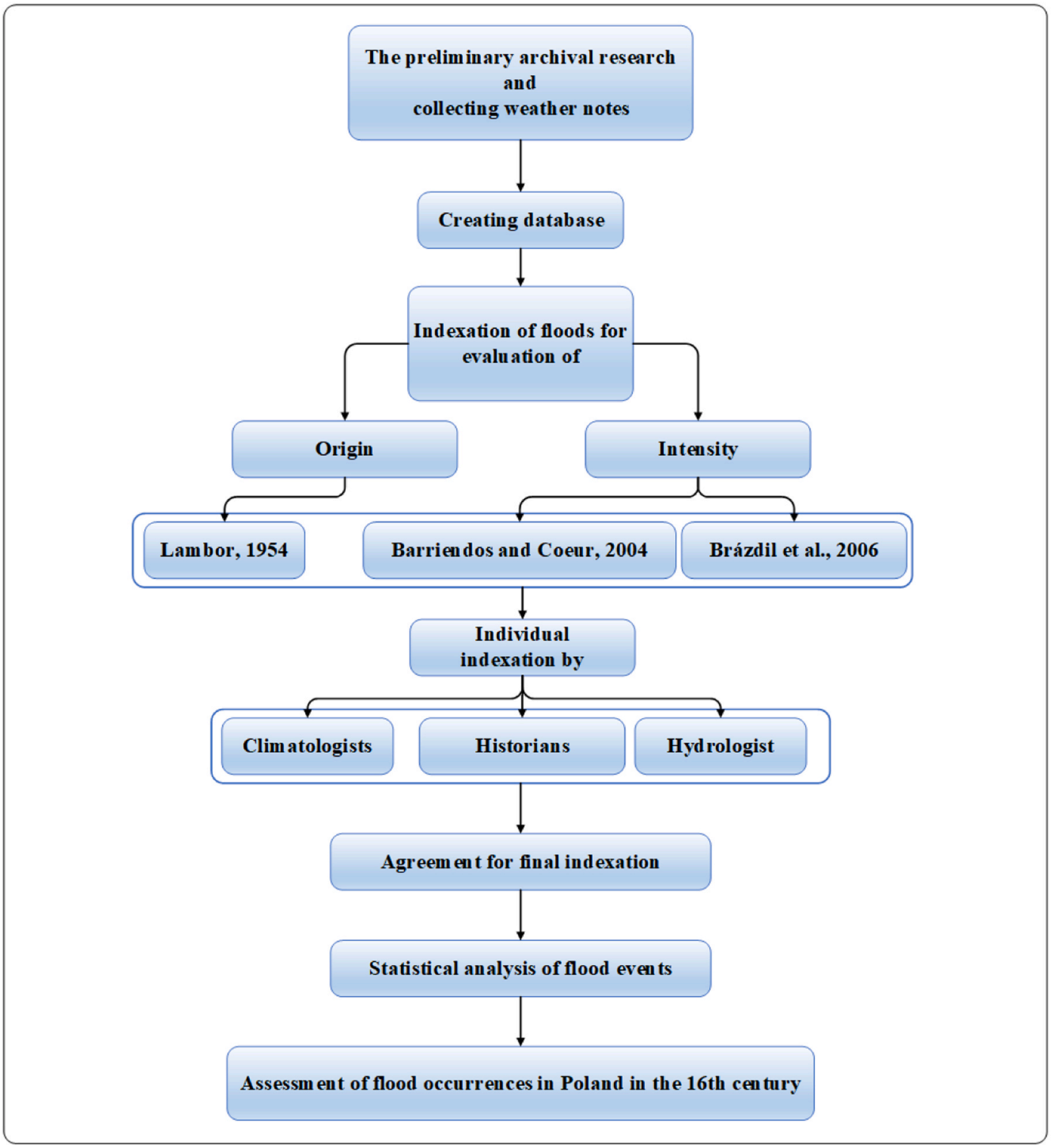

Fig. 2. Research elaboration procedure.

2. Study area, data sources and methods

In this study, the historical floods documented for the 16th century were analyzed for the contemporary area of Poland (Fig. 1), comprising six main regions; Baltic Coast and Pomerania, Masuria-Podlasie, Greater Poland, Masovia, Silesia, and Lesser Poland. However, in cases where historical sources did not specify a geographical location or only provided very general information, the flood was assigned to an additional category simply called "Poland". Additionally, the study area is divided into the three main river basins, namely, those of the Vistula, the Oder and the Baltic Coast (Fig. 1). To this last basin, we also included some areas of the north-eastern part of Poland that are formally parts of the Pregolya and Neman basins. This was mainly because of the small number of historical sources describing flood occurrences for these small areas. The most important and largest are the basins of the two longest Polish rivers, i.e., the Vistula (main cities: Warsaw, Cracow, Gdańsk, Włocławek, Toruń, Płock and Tczew) and the Oder (Krapkowice, Oława, Racibórz, Szczecin, Kędzierzyn-Koźle, Brzeg, Opole and Wrocław). We therefore also used these geographical references in our attempt to attribute the flood records to the three river basins. The reader should be aware that the area of Poland in the 16th century (Kingdom of Poland) was entirely different and only partly covered the area of modern-day Poland. For example, in the west, the Kingdom of Poland did not include West Pomerania or Silesia. Thus, a large part of the Oder River basin did not belong to the Kingdom of Poland. In the east, the Kingdom of Poland included the south-western part of Ukraine, while the north-eastern part, Podlasie, remained outside its borders. For this reason, it was necessary to use historical sources from provinces that were then outside the Kingdom of Poland, i.e. Silesia, much of Pomerania and Masuria, and even from neighboring countries when the information available in the sources was relevant to the study area.

In the first stage of this research, we created a comprehensive database (https://doi.org/10.18150/T3RXRI) of all flood events that occurred in Poland during the 16th century. This database contains more than 500 weather notes presenting information regarding original descriptions of flood events, regions where the flood occurred, the date (in some cases even days of onset) or seasons, documentary source, quality of source (1 – weak, 2 – moderate, 3 – high), and classifications of the intensity and origin of flood records (described in more detail later). A critical analysis of historical sources (a standard procedure utilized by historians) reporting on flood occurrences was performed. This analysis allowed us to choose the most reliable "first-hand" sources for the present work. In this study, we used 160 historical sources from various documentary sources, including handwritten (2), published (59), database (1) and secondary literature (98) sources. The majority were classified as high or moderate quality sources (80). For more detail, see Tables S1 and S2, which list all sources used and their quality. In cases where the same flood was described in several sources, the single or multiple weather notes taken for analysis were those from the highest-quality source or sources. In only a few cases, we used sources of the moderate or weak categories due to a lack of high-quality sources. Thus constructed, the database was used to calculate numerous statistics that would allow the characteristics of floods in Poland in the 16th century to be assessed.

In order to assess the intensity and origin of historical floods in Poland based on documentary evidence, the three most effective and widely used classifications have been used (see Tables S3–S5). The capability of these sources was approved in our previous study (Ghazi et al., 2023). It is important to add that other scientists have also successfully used these classifications for other European regions (Glaser et al., 2010; Retsö, 2015; Alcoforado et al., 2021; Benito et al., 2021).

It is worth mentioning that floods are difficult to distinguish from high-flow events based on documentary evidence due to possible uncertainties such as anthropocentric bias of testimonies. In this study, based on mentioned references for classification of floods, we only consider a weather note as referring to a flood when there is a clear use of the word "flood" in the description. In addition, to reduce these possible biases, all weather notes were discussed with team members with various aspects (historical, climatic and hydrological) to make a final agreement for events. Fig. 2 depicts the methodology used to conduct this research.

3. Results

The assessment of historical floods in Poland during the 16th century based on documentary evidence shows that 294 floods occurred (Table 1, Fig. 3). The results show that at least one flood was noted in every year of the century except the following 12 years: 1506, 1511, 1513, 1518, 1519, 1521, 1538, 1547, 1559, 1561, 1577, 1597. However, it can be emphasized that, in two years (1515 and 1570), the number of floods was extremely high, at 22 floods each. In other years, the number did not exceed ten cases and was usually below five (Fig. 3). There was also a clear preponderance of floods in the second half of the study period (1551–1600) rather than in the first (1501–1550). This pattern, however, was noted only in the floods occurring in the Oder River basin. By contrast, in the Vistula River basin, more floods occurred in the first half of the 16th century (Fig. 3). It is worth noting that, in the year 1515, floods were more frequent in the Vistula River basin than in the Oder River basin, whereas the opposite relationship was noted in the year 1570.

The spatial diversity of number of floods during the 16th century based on geographical location is illustrated in Figs. 4 and 5. The results showed that the number of floods was markedly greatest in Silesia (170) and next greatest in the region of Baltic Coast and Pomerania (46 floods). Slightly fewer floods than in the latter region occurred in Lesser Poland (35) and Greater Poland (29), while very few were detected for the regions of Masuria-Podlasie (4) and Masovia (1). Only for 11 floods was there no information detailing the area of their occurrences (Fig. 4, category "Poland").

In Silesia and Greater Poland, floods were more common in the second half of the 16th century, while in the other regions they were approximately equally distributed or slightly more frequent in the first half of the study period (Fig. 5).

In addition, as we mentioned earlier, the spatial diversity of floods was investigated for three river basins (Vistula, Oder and Baltic Coast). Analysis shows that, of these three, the most floods in Poland during the 16th occurred in the Oder River basin, with 202 floods (Fig. 3). In the Vistula River basin, floods were less than half as frequent (only 84), while in the Baltic Coast rivers basin they were noted very rarely – only nine times.

Table 1
Comparison of floods per year in Poland in 16th century in this research and other sources.

Current study (all of Poland)	Grześ (2008) (all of Poland)	Majewski (1993) (Vistula Delta only)	Bielański (1997) (Upper Vistula River only)	Mudelsee et al. (2003) (Oder River basin)	Kasprzak (2010) (Oder River basin)
1501 (3), 1502, 1503, 1504, 1505, 1507, 1508, 1509, 1510, 1512, 1514 (2), 1515 (22), 1516 (2), 1517 (2), 1520 (4), 1522 (2), 1523 (4), 1524 (4), 1525, 1526 (3), 1527, 1528 (5), 1529 (8), 1530, 1531 (2), 1532, 1533 (3), 1534 (2), 1535 (4), 1536,	1501, 1502, 1503, 1504, 1505, 1507, 1508, 1509, 1510, 1512, 1514 (2), 1515, 1516, 1517(2), 1520, 1522, 1523, 1524, 1526, 1527, 1528, 1529, 1530, 1531, 1532, 1533, 1534, 1535, 1536, 1537, 1539, 1540, 1541, 1542, 1543, 1544, 1545, 1546, 1548, 1549, 1550, 1551, 1552, 1553, 1554, 1555, 1556, 1557, 1560, 1562, 1563, 1564, 1565, 1566, 1567, 1568, 1569, 1570, 1571, 1572, 1573, 1574, 1575, 1576, 1578, 1579, 1580, 1581, 1582, 1583, 1584, 1585, 1586, 1587, 1588, 1589, 1590, 1591 (2), 1592, 1593, 1594, 1595, 1596, 1598, 1599, 1600	1501, 1505, 1507, 1509, 1512, 1513 *, 1514, 1515 (4), 1516, 1523, 1524, 1526, 1528, 1529 (3), 1534, 1540, 1542, 1543, 1544, 1553, 1557, 1560, 1562, 1565, 1570, 1571, 1577, 1584, 1595, 1599	1515, 1528 (3), 1533 (2), 1534 (2), 1535, 1541, 1542, 1549, 1557, 1562, 1570, 1571, 1580, 1593, 1598	1501, 1508, 1514, 1515, 1516, 1520, 1522, 1523, 1537, 1539, 1540, 1542, 1543 (2), 1548, 1549, 1550 (2), 1551 (2), 1556, 1564, 1565, 1568, 1570, 1572, 1578, 1579, 1584, 1586, 1591, 1593 (2), 1594, 1595 (2), 1598, 1599	1501, 1505, 1508, 1515, 1516, 1520, 1522, 1523, 1524, 1525, 1529, 1530, 1537, 1539, 1542, 1543 (2), 1548, 1550, 1551, 1556, 1559, 1560, 1563, 1566, 1567 (2), 1568, 1569, 1570, 1573, 1574, 1578, 1582, 1586, 1587, 1588, 1589, 1590, 1591, 1592, 1593, 1595, 1596 (2), 1598, 1599

(*continued on next page*)

Table 1 (*continued*)

Current study (all of Poland)	Grześ (2008) (all of Poland)	Majewski (1993) (Vistula Delta only)	Bielański (1997) (Upper Vistula River only)	Mudelsee et al. (2003) (Oder River basin)	Kasprzak (2010) (Oder River basin)
1537 (9), 1539 (3), 1540 (2), 1541, 1542 (3), 1543 (4), 1544 (2), 1545, 1546 (2), 1548 (2), 1549 (3), 1550 (5), 1551 (3), 1552, 1553 (2), 1554, 1555 (2), 1556, 1557 (3), 1558, 1559, 1560 (2), 1562 (2), 1563 (5), 1564 (4), 1565 (10), 1566 (2),					

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Table 1 (*continued*)

Current study (all of Poland)	Grześ (2008) (all of Poland)	Majewski (1993) (Vistula Delta only)	Bielański (1997) (Upper Vistula River only)	Mudelsee et al. (2003) (Oder River basin)	Kasprzak (2010) (Oder River basin)
1567 (4), 1568 (2), 1569 (3), 1570 (22), 1571 (3), 1572 (3), 1573 (7), 1574 (4), 1575, 1576 (2), 1578 (6), 1579 (2), 1580 (2), 1581, 1582, 1583, 1584 (4), 1585, 1586 (6), 1587 (5), 1588 (8), 1589, 1590, 1591 (5), 1592 (3), 1593 (8), 1594, 1595					

(*continued on next page*)

Table 1 (*continued*)

Current study (all of Poland)	Grześ (2008) (all of Poland)	Majewski (1993) (Vistula Delta only)	Bielański (1997) (Upper Vistula River only)	Mudelsee et al. (2003) (Oder River basin)	Kasprzak (2010) (Oder River basin)
(7), 1596 (2), 1598 (6), 1599 (3), 1600					

Key: () – number of floods in the mentioned year, if more than 1
* non-probable flood; no available source or wrong interpretation of source information; the flood was excluded from our database and statistical analysis

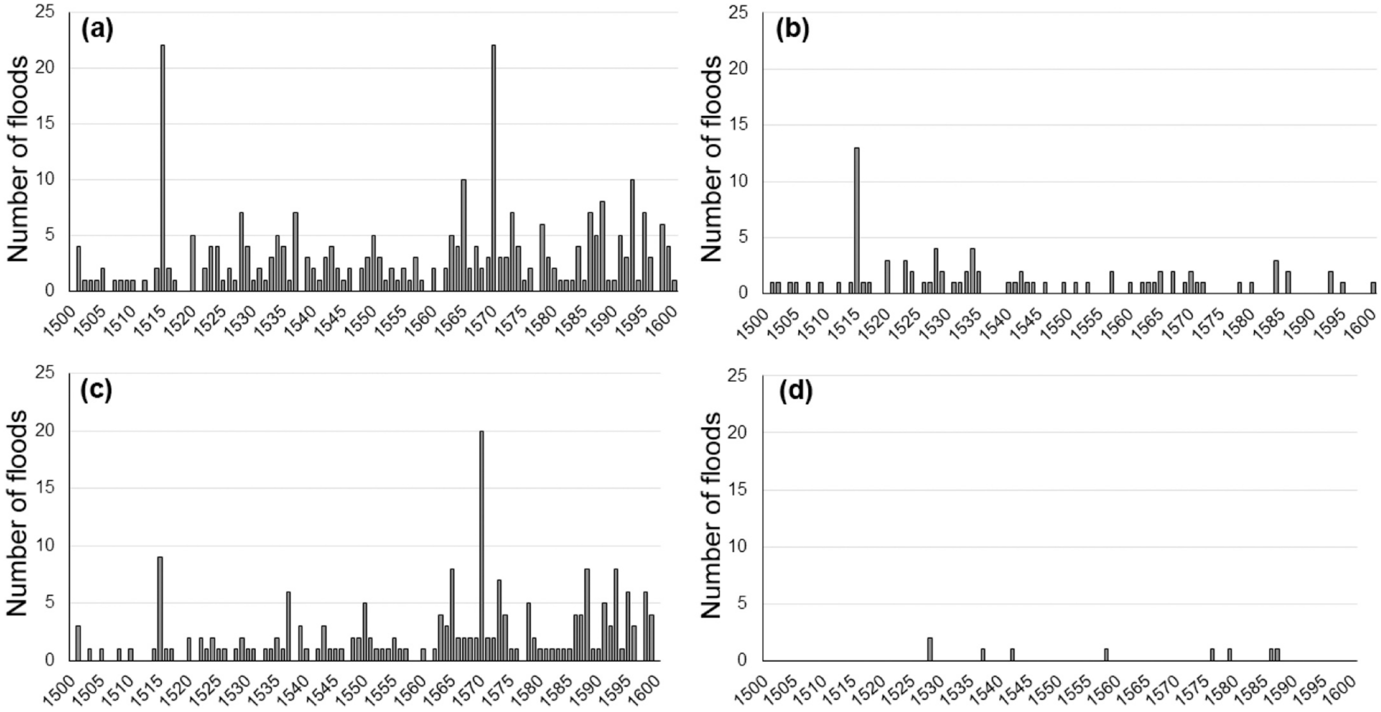

Fig. 3. Number of floods in Poland, AD 1501–1600: (a), all of Poland, (b) Vistula River basin, (c) Oder River basin, (d) Baltic Coast rivers basin.

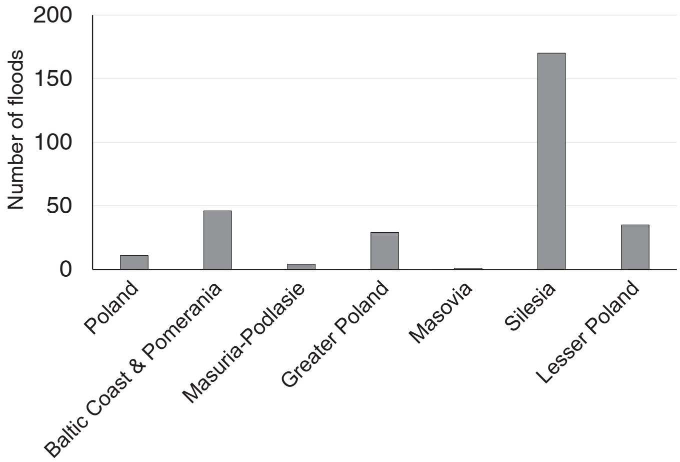

Fig. 4. Number of floods in Poland during the 16th century based on geographical location.

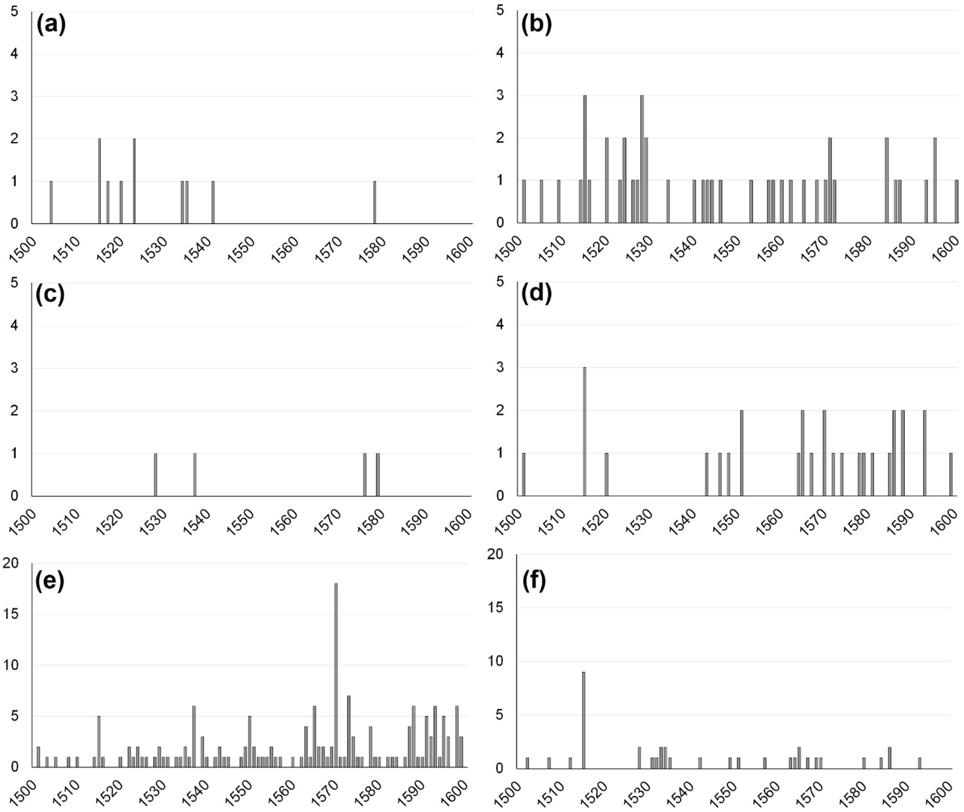

Fig. 5. Number of floods based on regions for the study period, (a) Poland, (b) Baltic Coast and Pomerania, (c) Masuria-Podlasie, (d) Greater Poland, (e) Silesia and (f) Lesser Poland. Note: Floods in Masovia region not shown because only one case was documented (see Fig. 3).

The results of classifications of intensity and origin of floods in Poland in the 16th century are shown in Fig. 6 and Table S6. Most of the floods were classified as "above-average, or supra-regional flood" (114) and "extraordinary" (223) based on the Brázdil et al. (2006b) and Barriendos and Coeur (2004) classifications, respectively. Based on these classifications, we also distinguished the extreme floods in Poland (see Table 2 for details). Their numbers ranged in the 16th century from 56 (category 3 according to the Brázdil et al., 2006b classification) to 61 (category 2 according to the Barriendos and Coeur, 2004 classification).

The estimation of main origin of floods based on the Lambor (1954) classifications indicated that "rain" and its sub-types (torrential, frontal and long-lasting rain) were the most frequent (157 cases) of floods in Poland during the 16th century. For 115 floods (39%) it was not possible to estimate the origin (N/A cases) due to lack of information. Additionally, the classification of floods

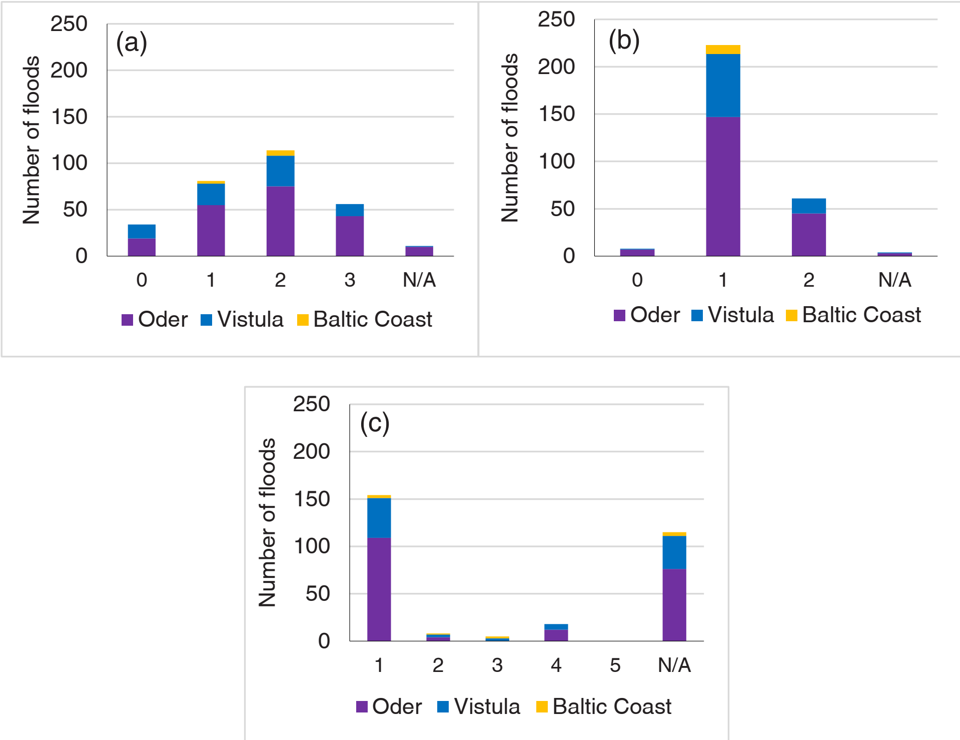

Fig. 6. Number of floods in Poland during the 16th century for river basins based on classifications of: (a) Brázdil et al. (2006b), (b) Barriendos and Coeur (2004), and (c) Lambor (1954). Key: N/A – information not available.

for river basins based on the mentioned sources is depicted in Fig. 6. As can be seen, the results generally agree with those presented for the area of all of Poland.

4. Discussion

This research provides a comprehensive assessment of historical floods in Poland, spanning floods registered in the 16th century in territory within the modern-day borders of Poland. Specifically, in addition to the list of flood occurrence records (time, duration, place) covering several times more flood occurrences than any previous study, we also provide detailed information about the historical sources used (including estimations of credibility), extracted weather notes, and indexation of flood intensity and origins (see Tables S3–S5). Moreover, the reliability of occurrence of a few floods listed in the Polish literature but not found in our preliminary archival research was checked using historical sources and included in our database when information about their occurrence was confirmed.

We compared the results of our research presented above against all existing works containing information about floods for all or parts of Poland for the 16th century (Majewski, 1993; Bielański, 1997; Mudelsee et al., 2003; Grześ, 2008; Kasprzak, 2010) (Table 1). The most complete information about floods in Poland in the 16th century, which is limited to lists of years of occurrence (without presenting sources and other characteristics), is provided in an unpublished work by Grześ (2008). Of the published sources, the noteworthy works are those of Majewski (1993), who gathered floods for the Vistula Delta (Baltic and Pomerania region), Bielański (1997) for the upper Vistula (Lesser Poland), and Mudelsee et al. (2003) and Kasprzak (2010) for the Oder River basin (Silesia region).

All the above-mentioned sources show a markedly lower frequency of floods in the 16th century than we documented in this paper. For example, the number of floods in Grześ (2008) is only 89, compared with the 294 floods in our database. Additionally, we could not confirm the occurrence of some floods that were available in the previous studies. This partly relates to the lack of detailed information and original sources in those studies. A good example is the flood of 1513, which is listed only in Majewski's (1993) source (Table 1). In the original historical source that Majewski (1993) cites to document this flood, there is no information about the occurrence of any flood. For this reason, we did not include this flood in our database. We also decided to check other notes about floods in the original historical sources cited in all the above-mentioned past publications to confirm the reliability of the floods listed there.

The assessment of floods for this study and their comparison against some neighboring countries, i.e., Austria (Traun and Salzach rivers), Czech Republic (the Vltava, Ohře, Elbe, Oder, Morava, Bečva, Dyje, Svratka, Opava, Lower Otava, and Upper Otava Rivers), Germany (the Elbe, Oder, Main, Upper Danube and Werra Rivers), and Sweden (the Norrstrom, Motala strom, and Gota alv Rivers) were carried on based on available sources (Table S7 and Fig. 7) (Glaser and Stangl, 2003; Mudelsee et al., 2003; Glaser and Stangl, 2004; Brázdil et al., 2005a; Mudelsee et al., 2006; Rohr, 2006; Brázdil and Kirchner, 2007; Rohr, 2007; Glaser et al., 2010; Brázdil

Table 2
Comparison of extreme floods in the 16th century for Poland, Czech Republic and Germany.

Current research*	Poland (Kowa-lewski, 2006)	Czech Republic		Germany	
		Vltava River (Prague) (Brázdil et al., 1999; Elleder, 2015 (Brázdil et al., 1999)	Upper Elbe River (Děčín) (Brázdil et al., 1999)	*Oder River*Elbe River (Mudelsee et al., 2003)	Other rivers (Main, and Saale) (Brázdil et al., 1999)
1501 (2), *1508*, *1512*, **1515 (6), 1522, 1524 (2), 1526, 1527, 1528 (2), 1533 (2), 1534, 1535, 1536, 1537 (2), 1540**, *1549*, **1550, 1551, 1555, 1563, 1564 (2), 1565, 1566, 1567 (2), 1569, 1570 (3)**, *1570*, **1572 (3), 1578 (3), 1584, 1585, 1586 (2), 1593 (2), 1595, 1596**, *1596*, **1598 (3)**	1501, 1515, 1564, 1570, 1593, 1598	1501, 1504, 1515, 1531, 1537, 1564, 1566, 1567, 1568, 1569, 1570, 1575, 1582, 1587, 1598	1501, 1504, 1531, 1537, 1559, 1565, 1566, 1569, 1570, 1573, 1578, 1579, 1593, 1595, 1598 (2),	1501, *1501, 1515, 1565,* 1566, 1570, *1595,* 1595, 1598, 1599	1501, 1524, 1546, 1551, 1552, 1555, 1563, 1569, 1571, 1582, 1584,

*Italic font indicates a category 2 flood (catastrophic) based on Barriendos and Coeur (2004); bold font indicates common floods based on Brázdil et al. (2006b) (category 3) and Barriendos and Coeur (2004).

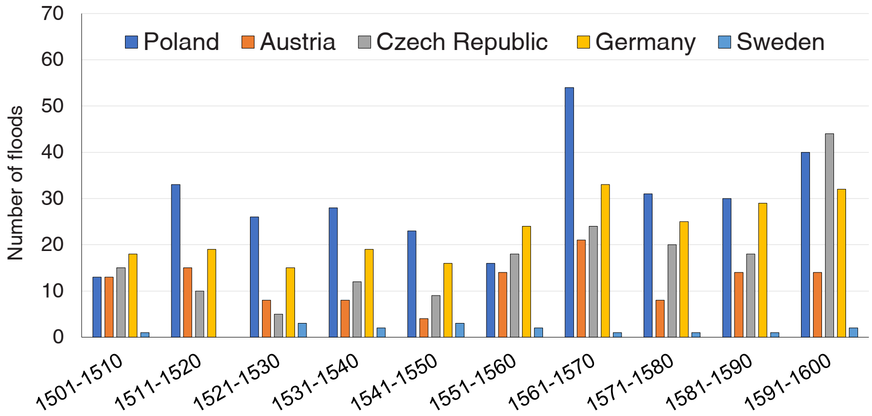

Fig. 7. Comparison of numbers of floods for Poland, Austria, Czech Republic, Germany and Sweden in the 16th century.

et al., 2011; Retsö, 2015; Blöschl et al., 2020). However, the reader should be reminded of possible biases related to the number of available sources and differences in spatial coverages in this study and other studies. Consequently, we present only the relative frequencies of floods occurring simultaneously in both Poland and these analyzed countries, in order to reduce the influence of some biases.

In general, based on results from Fig. 7, excluding the decades 1501–1510, 1551–1560 and 1591–1600, the number of floods was greater in Poland than in other countries. By contrast, in all periods, the number of floods is less in Sweden than in other countries. This is partly related to the climate of Sweden differing (via the influence of the Scandinavian mountains) from that of the other countries being compared. Statistical assessments demonstrate that about 87% and 80% of floods that occurred in Sweden and Austria, respectively, were also noted in Poland. These values for the Czech Republic and Germany were slightly smaller but still high, at 78% and 71%, respectively.

The analysis of comparison of main origin of floods in Poland and in some neighboring countries reveals that the most frequent reason was rainfall and it subtypes (Table 3). Only floods in the Elbe River in Germany differed in this regard, being caused more by ice jam (33%) than any other single cause. It is clear that a relatively large number of historical sources, give no sufficient information regarding the origin of floods (except Austria and Sweden). The origin of floods could not be estimated for 37% of sources in Poland, 40–45% in Germany and as much as 65–80% in the Czech Lands (Table 3).

Both the scientific community and the public are always concerned about extreme floods because of their various catastrophic impacts on human lives and economics. Therefore, the occurrence of extreme floods found in this research was compared against other available sources of floods for Poland and neighboring countries (Table 2). Again, it should be noted that there are possible biases in these results due to differences in the selection of criteria for the classification of extreme floods between this research and other studies. In the Polish literature, only Kowalewski (2006) has listed extreme floods. The results showed that only six extreme floods are available in this source for the 16th century, in comparison with the 59 floods listed in the present study. Elleder (2015) and Brázdil et al. (1999) ascertained 15 floods for the Vltava River in Prague, Czech Republic. Mudelsee et al. (2003) estimated four floods for the Oder and seven for the Elbe in Germany, while the number of extreme floods for other rivers (the Main and the Saale) in Germany was 11 (Brázdil et al., 1999). Additionally, 16 extreme floods were recorded for the Upper Elbe – Děčín in the Czech Republic (Brázdil et al., 1999).

We also compared the results of occurrences of floods in Poland in the 16th century against the results for the medieval period (11th–15th centuries) from previous research (Ghazi et al., 2023). In general, the number of flood occurrences in Poland was more in the 16th century (294 floods) than the total for the 11th–15th centuries (166 floods). These results confirm previous studies' results for other regions in Europe, which also revealed the number of floods being greater in the 16th century than in the entire medieval period (Benito et al., 2003; Mudelsee et al., 2003; Grześ, 2008; Blöschl et al., 2020). This is only partly connected with the greater detection of floods in the 16th century than in medieval times due to the greater number and detail of 16th century sources.

Table 3
Relative frequency (%) of main origin of floods in Poland and selected neighboring countries.

Category	Current study (Poland)	Austria		Czech Republic			Germany		Sweden
		Salzach River	Traun River	Vltava	Elbe	Ohře	Elbe	Oder	
Rain, subtypes	53	100	87	24	22.5	12	19	39	87.5
Snowmelt	4	–	6	6	2.5	–	3	–	12.5
Ice jam	5	–	7	–	10	8	33	21	–
Storm	1	–	–	–	–	–	–	–	–
N/A	37	–	–	70	65	80	45	40	–

Another interesting finding is that, in the 11th–15th centuries, the most floods were recorded in the Vistula River basin, while in the 16th century they were more common in the Oder River basin. On the other hand, there was no difference between the two basins in the estimation of the intensity of floods for either period. For both periods, the category of "above average or supra-regional floods" according to the classification of Brázdil et al. (2006b) and "extraordinary" based on the Barriendos and Coeur (2004) classification accounted for more than 50% of the registered classifications. The classified origin of floods for both periods also confirms that rain and it sub-types were the most common reason for occurrences of floods in Poland during the mentioned periods.

A spatial variability was found in flood occurrences in the study regions. The number of floods was higher in Silesia than in other regions, while the numbers of floods in the Masuria-Podlasie and Masovia regions were lower. This is partly related to the number of sources and weather notes, where the weather notes available in the historical sources for flood occurrences in Silesia account for 61% of all records, which is significantly more than those for Baltic Coast and Pomerania (14%), Lesser Poland (11%), Greater Poland (10%), Masuria-Podlasie (1%) and Masovia (0.2%). In addition, much of the Silesia region is located in the Sudeten Mountains, where the density of rivers is greater than in the lowlands. These facts increase the Silesia region's vulnerability to extreme events in comparison with other regions in Poland.

Although the documentary evidence provides valuable information about the occurrences of various extreme events, these types of data mainly depend on subjective interpretation and are thus to be used mindfully. In addition, the reader should be aware about possible limitations in the reconstruction of historical floods based on documentary evidence. In deriving historical flood events, there are various biases such as availability and quality of sources, and anthropogenic biases in the descriptions of events. A good overview of all kinds of limitations of documentary evidence is given by Brázdil et al. (2005b).

4. Conclusions

The review of the literature clearly showed that the 16th century was a unique century in terms of the high numbers and intensities of floods in Europe, including Poland. That is why this century has great importance for historical hydrology evaluation. The presented comprehensive assessment of historical floods in Poland during the 16th century based on documentary evidence improves the existing knowledge for both the study area and Central Europe. To achieve this goal, a comprehensive database was first created, encompassing indexation of the intensity and origin of each flood. This was the first such indexation for the study area. It is worth noting that the reconstruction of historical floods in Poland in the 17th–18th centuries, will significantly fill the knowledge gap in the assessment of historical floods in Poland in the period before instrumental data.

The main output and the summary of this study are as below:

1. Based on documentary evidence, 294 floods occurred in Poland in the 16th century.
2. Most of the floods were recorded in the Oder River basin (202 floods, 69%). Significantly fewer (84 floods, 28%) occurred in the Vistula River basin, and only nine floods (3%) in the basin of the Baltic Coast rivers.
3. The regions most vulnerable to floods during the 16th century in Poland were, in order: Silesia (170 floods, 58%), Baltic Coast and Pomerania (46 floods, 16%), Lesser Poland (35, 12%), Greater Poland (29, 10%), Masuria-Podlasie (4, 1%), and Masovia (1, 0.3%).
4. Based on the (Brázdil et al., 2006b) classification, "Above-average, or supra-regional flood" (114 cases) was the most common index for intensity of floods, while the "extraordinary" index (223 cases) was more common for the Barriendos and Coeur (2004) classification.
5. The main origins of floods in Poland in the 16th century was rain and its subtypes (157 cases), 1a) torrential (38), and 1c) long-lasting, territorially widespread rains (35 cases).
6. Based on the criteria for the classifications used, we distinguished 56 extreme floods according to Brázdil et al. (2006b) and 61 extreme floods according to Barriendos and Coeur (2004) (Table 2).
7. The floods in Poland have good spatial coherency with neighboring countries. The results show that almost 87%, 80%, 78%, and 71% of floods that occurred in Sweden, Austria, Czech Republic and Germany, respectively, were also recorded in Poland (Table 1 and Table S7).

CRediT authorship contribution statement

Babak Ghazi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Rajmund Przybylak:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Funding acquisition, Project administration, Validation, Supervision, Writing – original draft, Writing – review & editing. **Piotr Oliński:** Investigation, Data curation, Validation. **Waldemar Chorążyczewski:**, Data curation, Validation. **Aleksandra Pospieszyńska:** Data curation, Validation, Software, Visualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The dataset of flood records for Poland in the 16th century is available at (https://doi.org/10.18150/T3RXRI). Other data used in this research are available from the corresponding author, upon reasonable request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101597.

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A comprehensive study of floods in Poland in the 17th–18th centuries

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ABSTRACT

Study region: Poland, with the regions of Baltic Coast and Pomerania, Masuria-Podlasie, Greater Poland, Masovia, Silesia, and Lesser Poland located in the basins of the Baltic Coast rivers, the Vistula River and the Oder River.
Study focus: This study focused on completing the documentation of historical floods in Poland before the 19th century and providing a valuable source for historical hydrology studies in Europe. To this end, a comprehensive database of all floods for the 17th–18th centuries was used, that was based on documentary evidence from 293 sources and 978 weather notes describing all flood occurrences.
New hydrological insights for the region: The finding of this study revealed the occurrences of 678 floods, including 37 new cases that have been discovered and documented only in this research. Spatial analysis of the results revealed that most of the floods occurred in the Vistula River basin. The number of floods by season was greatest for summer (JJA) (47 %) and smallest for autumn (7 %). Investigation of the origin of floods indicated that rain was the main factor contributing to occurrences of floods in Poland (38 %). The estimation of the intensity of floods showed that most of the floods were "smaller, regional floods" (257 cases) based on the Brázdil et al. (2006b) classification and "extraordinary" (501 cases) in the Barriendos & Coeur (2004) classification.

1. Introduction

Climate change has increased the public and scientific communities' concerns about the increasing frequency of floods in river basins globally (Rohde, 2023; Rottler et al., 2023). Floods are among the most frequent natural disasters. In terms of various economic and human losses, floods have the most significant catastrophic impacts on human societies and the environment. Europe has experienced numerous devastating floods in the last few decades, resulting in considerable economic losses (Blöschl et al., 2019). Therefore, to reduce flood hazard risk, long-term comprehensive studies are necessary (Brunner et al., 2020; Merz et al., 2021). To this aim, it is crucial to uncover the intensity and genesis of floods in past centuries (Hundecha et al., 2020). Considering the limited time

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frame of instrumental hydrological observations, historical hydrology occupies a position at the interface between hydrology and history (Brázdil et al., 2006b). Reconstruction of historical floods can provide a better understanding of flood hazards over the long-term perspective and improve the ability to predict future events (Blöschl et al., 2017; Wilhelm et al., 2019). Multiple sources from historical hydrology provide useful information about climate variability over past centuries that predate the availability of instrumental records (García-Barrón et al., 2023). Documentary evidence constitutes a reliable form of proxy data in terms of providing credible information about temporal and spatial trends of past climatic and hydrological events (i.e., floods and droughts) (Kjeldsen et al., 2014). In recent decades, European flood records have been reconstructed using diverse documentary evidence (Cœur and Lang, 2008; Retsö, 2015; Blöschl et al., 2020; García-Barrón et al., 2023). Studies analyzing the history of floods in Poland in the last millennium, in particular before the 19th century are written almost exclusively in the Polish language and are usually limited to general information about the year or region(s) of floods. Moreover, majority of these studies are focused on the last 200 years.

Cyberski et al. (2006) used documentary evidence to review the history of floods on the Vistula River from AD 988–2006. The authors derived historical floods for the Upper Vistula, Middle Vistula and Lower Vistula from documentary resources in the pre-instrumental period. The results showed that the rivers in the Carpathian tributaries (Soła, Dunajec and Skawa Rivers) were the main contributors to flood events on the Upper Vistula. On average, the Soła River made the greatest contribution to flooding of the Upper Vistula connected with the topography, geology and precipitation conditions of drainage basins. The history of floods for the last millennium limited to Upper Vistula was also presented by Nachlik and Kundzewicz (2016). A study of floods for period 1799–2001 presented by Fal and Dąbrowski (2001) revealed that 64 % of them in the Middle Vistula were caused by snowmelt. It is reported that, on the Middle Vistula, snowmelt-induced flood events happened mainly in March, April and February, with these months accounting for 44 %, 28 % and 16 %, respectively, while rain-induced floods were most common in July (29 %), August (24 %) and June (20 %). On the other hand, the majority of historical floods in the Lower Vistula occurred due to their freezing in winter and the break-up of ice jams in spring (Grześ, 1991; Embleton and Embleton-Hamann, 1997). Although these studies provide valuable information about the history of floods in Poland, they lack detailed information such as description of events and the intensity and primary cause of floods. Unlike for Poland, for other European countries such as Austria, Czech Republic, Hungary, Germany, Sweden and Switzerland there exist previous studies that have assessed historical floods (Pfister, 2002; Brázdil et al., 2005b, 2006a, 2011; Rohr, 2006, 2007; Retsö, 2015).

For the reasons described above, the scientific literature about floods in Poland, including in historical times, is rarely known by the non-Polish scientific community. To fill this knowledge gap, we have already created two comprehensive databases – one for the 11th–15th centuries (https://doi.org/10.18150/WD18XJ) and one for the 16th century (https://doi.org/10.18150/T3RXRI), and we have reconstructed the history of floods in Poland before the 17th century (Ghazi et al., 2023a, 2023b). However, there is still no comprehensive study of floods in the 17th–18th centuries in Poland. The aim of this study is to show the results of our work focusing on flood reconstructions for Poland for the 17th–18th centuries. As a result, the entire history of flood occurrences in Poland will be known for the pre-instrumental period in hydrology, which started in Europe (including Poland) usually at the beginning of the 19th century (Brázdil et al., 2006b). The results of this and two previous studies (Ghazi et al., 2023a, b) improve knowledge on the historical climatology and hydrology of Central Europe.

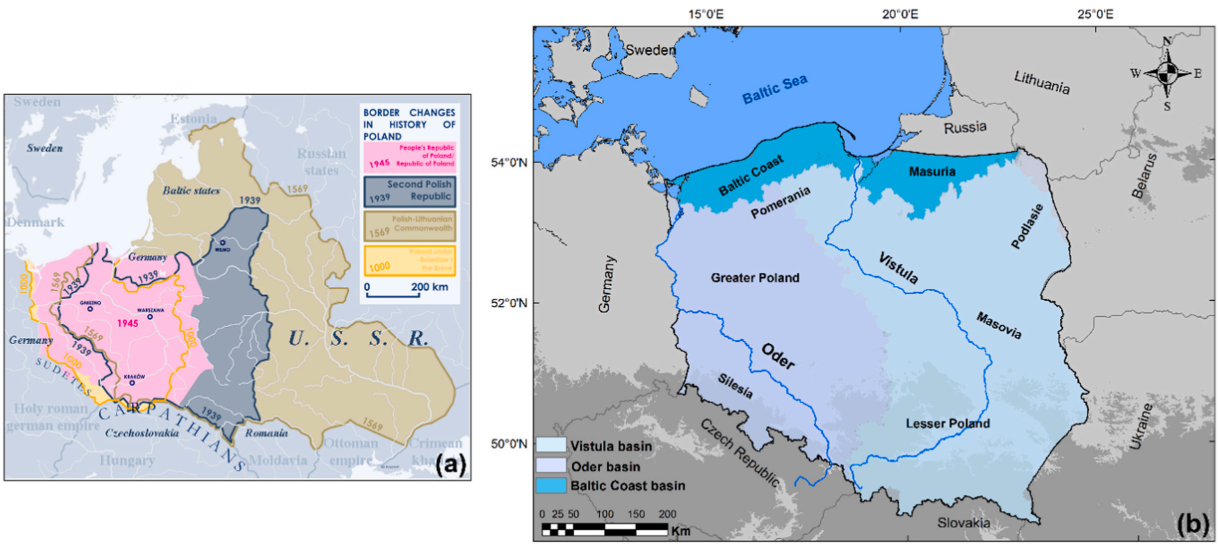

Fig. 1. (a) Changes to the borders of Poland in historical times (source: https://commons.wikimedia.org/wiki/File:Border_changes_in_history_of_Poland.png) (b), Geographical location of contemporary Poland and main river basins.

Table 1
Years of flood occurrences in Poland for the 17th–18th centuries.

Current study (all of Poland)	(Grześ 2008) (all of Poland)	Majewski (1993) (Vistula Delta only)	Bielański (1997) (Upper Vistula River only)	Mudelsee et al. (2003) (Oder River basin)	Kasprzak (2010) (Oder River basin)	(Blöschl et al. 2020)	
						Middle Oder River	Vistula River
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 (7), **1636**, **1638**, 1639 (3), 1644, **1645**, 1646 (4), **1647 (3)**, 1648 (2), 1649 (5), 1650 (11), 1651 (9), 1652 (7), 1653, 1654, 1655 (6), 1656 (4), 1657 (3), 1658 (4), 1659 (4), 1660 (4), 1661 (5), 1662 (10), 1663 (9), 1665 (5), 1666 (3), 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 (10), 1699 (2), 1700 (2), 1701 (2), 1702 (13), 1703 (17), 1706, **1707**, 1708 (3), 1709 (12), 1710 (2), 1711 (2), 1712 (7), 1713 (18), 1714 (9), 1715 (10), 1716, 1717 (5), 1718 (8), 1719 (3), 1720 (2), 1721 (4), 1723 (4), 1724, **1725 (2)**, 1729 (7), 1730	1601, 1602, 1605, 1606, 1607, 1611, 1612, 1613, 1622, 1624, 1635, 1639, 1651, 1652, 1657, 1661, 1666, 1668, 1669, 1670, 1672, 1673, 1674, 1675, 1676, 1677, 1679, 1680, 1689, 1693, 1700, 1706, 1709, 1713, 1716, 1717, 1718, 1719, 1720, 1721, 1724, 1729, 1731, 1736, 1737, 1738, 1741, 1742, 1743, 1744, 1745, 1749, 1750, 1753, 1757, 1761, 1764, 1765, 1767, 1774, 1778, 1780, 1782, 1783, 1784, 1785, 1786, 1789, 1792, 1794	1602, 1606, 1613, 1621, 1624, 1633, 1639, 1646, 1651, 1652, 1567, 1658, 1659, 1660, 1661, 1662, 1663, 1668, 1669, 1671, 1672, 1674, 1675, 1676, 1677, 1679, 1680, 1693, 1695, 1708, 1713, 1714, 1717, 1718, 1719, 1731, 1734, 1739, 1745, 1749, 1765, 1774, 1775, 1784, 1786,	1605, 1621, 1650, 1652, 1655, 1656, 1662, 1670, 1671, 1687, 1697, 1736, 1774, 1775	1605, 1606, 1612, 1613, 1614, 1616, 1621, 1624, 1625, 1628, 1630, 1633, 1634, 1644, 1646, 1648, 1651, 1652, 1654, 1655, 1658, 1659, 1662, 1663, *1664*, 1665 (2), 1667, 1672, 1674, 1675, 1679, 1680, 1685, 1687, 1688, 1689, 1692, 1693, 1694, 1695, 1696, 1698, 1699, 1706, 1708, 1709, 1712, 1713, 1715, 1718, 1729, 1730, 1731, 1736 (2), 1737 (3), 1749, 1751, 1770, 1771, 1775, 1779, 1780 (2), 1783, 1784, 1785, 1789, 1794, 1798, 1799	1604, 1609, 1613, 1649, 1650, 1652, 1653, 1654, 1667, 1685, 1686, 1691, 1694, 1701, 1702, 1703, 1708, 1709, 1710, 1711, 1713, 1714, 1723, 1729, 1736, 1751, 1759, 1766, 1767, 1773, 1778, 1780, 1783, 1785, 1786, 1792, 1795 (2), 1797	1622 1628 1652 1685 1709 1710 1711 1712 1713 1732 1734 1735 1736 1737 1738 1739 1740 1741 1742 1743 1744 1785	1605 1621 1649 1650 (2) 1651 1652 1655 1656 (2) 1657 1658 1659 1661 (2) 1662 (4) 1663 (3) 1665 1667 1668 1670 1671 1675 (2) 1675 1687 1688 1690 1695 1697 1736 1772 (2) 1774 (3) 1775 1785 (2) 1786 1787 (2) 1795

(*continued on next page*)

Table 1 (*continued*)

Current study (all of Poland)	(Grześ 2008) (all of Poland)	Majewski (1993) (Vistula Delta only)	Bielański (1997) (Upper Vistula River only)	Mudelsee et al. (2003) (Oder River basin)	Kasprzak (2010) (Oder River basin)	(Blöschl et al. 2020)	
						Middle Oder River	Vistula River
(2), 1731(9), 1732 (3), 1734 (4), 1735 (6), 1736 (26), 1737 (7), 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), 1668, **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							

Explanations:
() – more than one flood in the year is given
Bold font – new floods not present in other previous studies
Italic font – flood was classified as “high-water” in our study

2. Study area, materials and methods

The borders of Poland have undergone various changes throughout history. In past centuries, the state borders of Poland have differed from those of the contemporary era (see Fig. 1a). Therefore, to conduct a comprehensive study for assessment of flood events in Poland, we used the current boundary of this country. The current area of Poland is divided into six main regions (Fig. 1b): Baltic Coast and Pomerania, Greater Poland, Masovia, Masuria-Podlasie, Lesser Poland and Silesia. These six main regions are parts of three main river basins in Poland: those of the Vistula River, the Oder River and the Baltic Coast rivers. Thus, we identified all flood events based on these six main regions and distinguished the main river basin. In a few cases, due to the lack of information about the region (s) where floods occurred, the miscellaneous category “Poland” was used to describe the area of flood occurrences.

For comparison purposes, the methodology in this research is identical to that which we used in our previous studies analyzing flood occurrences in Poland in the period 1001–1600 (Ghazi et al., 2023a, b). To summarize, the following procedure was utilized: 1) construction of a comprehensive database (https://doi.org/10.18150/VLPAFG) of all floods for the 17th–18th centuries, including information about region(s), place, river basin, date of event (year, month and day if available), weather notes, sources, source quality and indexation of intensity and origins of flood, 2) evaluation of sources based on their quality (1 – weak, 2 – moderate, 3 – high) to select best source(s) and weather note(s) for flood events in order to use them for individual classification purposes, 3) independent classification of every flood made by two historians, two climatologists and one hydrologist, 4) arrangement of the final classification in a team discussion, 5) comprehensive statistical analysis of obtained results.

The classification of sources is as follows: 1 – weak (when the information was taken from secondary literature instead of the original source); 2 – moderate (when the information is written from other centuries than when the flood occurred or the description of the event differed from that contained in a note written contemporaneously with the event); 3 – high (when information was written in a source contemporaneous to the flood event and it is precise with exact information about the event). In this research, we used 293 sources (for details see Table S1) and 978 weather notes describing all flood occurrences (https://doi.org/10.18150/VLPAFG).

However, for classification of floods' intensity and origin, we used 700 of the weather notes that are the most reliable and/or describe floods in greater detail (Table S2). As results from this documentation, various kinds of sources, both published (including original sources and secondary literature) and unpublished (handwritten, databases), have been used to assess historical floods. The quality of these sources was evaluated by historians using critical source analysis. Further, the most reliable sources were selected in this procedure for classification of the intensity and origin of floods.

For classification of origin of floods, we used the method given by Lambor (1954), while their intensity was estimated using criteria given by (Barriendos and Coeur, 2004; Brázdil et al., 2006b)). According to Lambor's (1954) classification, the primary causes of floods in Poland are rain (torrential and frontal rain), snowmelt, winter (ice jam and shuga), and storms. Barriendos and Coeur (2004) proposed flood classification according to the destructive impact, intensity and scale of events. In their classification, floods were categorized into ordinary, extraordinary and catastrophic floods. The classification of floods proposed by Brázdil et al. (2006b) is slightly modified from that originally introduced by Sturm et al. (2001). Four categories were distinguished; 0 – a flood; 1 – a small, regional flood; 2 – an above-average or super-regional flood; and 3 – a disastrous flood on a large scale (see Table S3–S4). The intensity (size) estimation of floods based on documentary evidence is usually very challenging because the available information has a qualitative character. For this reason, we used the two mentioned classifications to overcome the possible uncertainties in addressing the intensity of floods. These classifications have been successfully used and approved both in our previous studies for Poland (Ghazi et al., 2023a, 2023b) and in other studies analyzing flood occurrences in different parts of Europe (Glaser et al., 2010; Bhat et al., 2019; Benito et al., 2021).

In the flood database, in some cases, there are several floods in the same year. In that case, when there is clear information in the weather note(s) about flood occurrences in various rivers, we assume them to be separate floods. On the other hand, when floods occurred in the same year but in different months or seasons on the same river, we distinguished those separated by an interval greater than 7 days to have been separate floods.

To distinguish the "flood" and "high-water" events, in the classification of the intensity of floods, we assumed an event was a "high-water" if it was classified as category "0" (ordinary flood) using the Barriendos and Coeur (2004) classification (see Table S3).

3. Results

A comprehensive assessment of floods in Poland in the 17th–18th centuries demonstrated that, overall, 678 floods occurred (Table 1 and S5, Fig. 2). Most of them occurred in the Vistula River (349) and Oder River (321) basins, while only a few were recorded in the Baltic Coast rivers basin (8). In the study period, the highest number of floods (>10 cases) occurred in the following years; 1650 (11), 1675 (18), 1702 (13), 1703 (17), 1709 (12), 1713 (18), 1736 (26) and 1774 (12). Except for the last year, all occurred in a flood-rich period that we locate between 1650 and 1740 (Fig. 2a). In this time, as many as 417 (61%) floods were registered in the historical sources. It is interesting to note that the distinguished flood-rich period in Poland contains a relatively "dry" interval in the Vistula

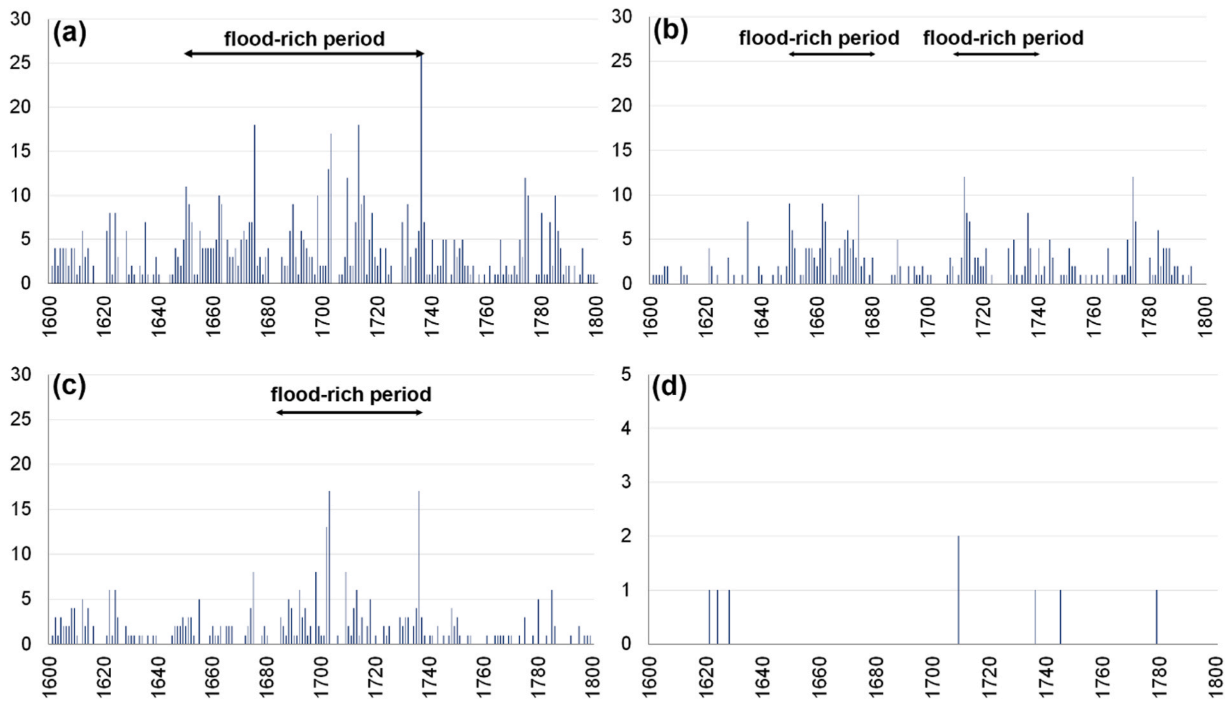

Fig. 2. Number of floods in Poland, AD 1601–1800: (a), All river basins in Poland, (b) Vistula River basin, (c) Oder River basin, (d) Baltic Coast rivers basin.

River basin; thus, the floods within this period were most frequent in the periods 1650–80 and 1710–40. On the other hand, in the Oder River basin the flood-rich period started later (in 1690) than it did on average in Poland, but ended at the same time (1740) (Fig. 2b, c). An increase in flood occurrences in the Vistula River basin is also seen in the period 1775–90.

To show the spatial variability of floods recorded in Poland in the 17th–18th centuries, their frequencies are presented also for its six main historical-geographical regions (Fig. 3). In general, the most floods were recorded in the Silesia and Baltic Coast and Pomerania regions which account for 246 and 166 floods, respectively. The numbers of floods in Lesser Poland (145) and Greater Poland (69) were also relatively high, while the numbers of floods were small in Masovia (38) and especially small in Masuria-Podlasie (6). For only eight floods, did we not find any detailed information about the place/regions of their occurrence (category "Poland"). The year-to-year course of frequency of flood occurrences stratified into historical-geographical regions is shown in Fig. 4.

Based on the results presented in Fig. 4, flood-rich periods are clearly seen mainly in three regions (Baltic Coast and Pomerania, Silesia, and Lesser Poland). In the Baltic Coast and Pomerania region, two such periods can be distinguished (ca 1660–1680 and 1710–1745) when 35 (21 %) and 57 (34 %) floods occurred, respectively. In Silesia region, floods were most frequent in the period from about 1690–1745 (113, 46 %). Two flood-rich periods (ca 1650–1680 and 1775–1790) are also present in the Lesser Poland region. It is important to note that the timings of these regional flood-rich periods show good correspondence with the distinguished flood-rich period for the whole of Poland (compare Figs. 2a and 4b, e and f).

In the assessment of the database of registered floods in Poland in the 17th–18th centuries, for almost 76 % of the records, we identified the month that floods occurred. The analysis of the frequency of floods occurrences in various months of the year demonstrated that the most occurred in July (22 %), while they were fewest in October (0.5%) (Fig. 5). In general, a bimodal distribution can be noted, with maxima of flood occurrences in the periods Jun–Aug (primary) and Jan–Apr (secondary). Therefore, in terms of seasons, the predominant period of floods in Poland in the study period was summer (JJA) (47 %). The frequencies of floods in spring (MAM) and winter (DJF) were each about half that, accounting for 26 % and 21 %, respectively. Decidedly, the smallest number of floods was registered for the autumn (SON) (6 %).

Barriendos and Coeur (2004) distinguished category "0" (ordinary floods), which they described as: 'In-bank flow, no damage, water discharge can increase but without overflowing' (see Table S3). Such cases were included to our database but were not labeled as floods (see Table S6). The occurrence of high-water levels in rivers in Poland in the study period reached 43 cases. Most were noted in the Oder River basin (32). On the other hand, there times fewer high-water levels (11) were registered in the Vistula River basin.

Results of the assessment of the intensity and origin of floods based on the classifications mentioned in the previous subsection, are presented in Fig. 6. According to the Brázdil et al. (2006b) classification of intensity of floods, the most common categories were "Smaller, regional flood" with 257 floods and "Above-average, or supra-regional flood" with 209 cases. About two to three times less frequent were floods described as "Above-average, or supra-regional flood on a disastrous scale" (119 cases) and "flood" (93). Based on the Barriendos and Coeur (2004) classification, most of the floods were attributed to the "extraordinary" category (501 cases). Quite a large number of "catastrophic" category floods was also noted (167 cases). Only ten records belong to the "ordinary" category based on this classification, which describes not a true flood, but a high water level.

Results of the assessment of the origin of floods using the Lambor (1954) classification revealed that rain was the main contributing factor for the most occurrences of floods in Poland in the 17th–18th centuries (Fig. 6). Overall, 275 floods were caused by rain, of which, 64 were related to torrential rain, 3 to frontal rain and 46 to long-lasting, territorially widespread rain. In 162 cases, there is no detail about rain sub-types. The second most important reason for floods was the occurrence of ice jams on rivers. We found also that five floods in Poland in the study region were caused by intentional human activity (usually the destruction of the embankments). Therefore, we slightly modified the Lambor (1954) classification of origin of floods (see Table S4).

4. Discussion

Retrieving historical floods from documentary evidence, is a challenging task in historical hydrology research due to the various uncertainties and limitations. These uncertainties in documentary evidence are mainly related to their quality and to human subjectivity in describing the historical extreme events (Brázdil et al., 2005c). However, to provide a comprehensive assessment floods in Poland in the 17th–18th centuries, we conducted this research based on documentary evidence that had already been successfully

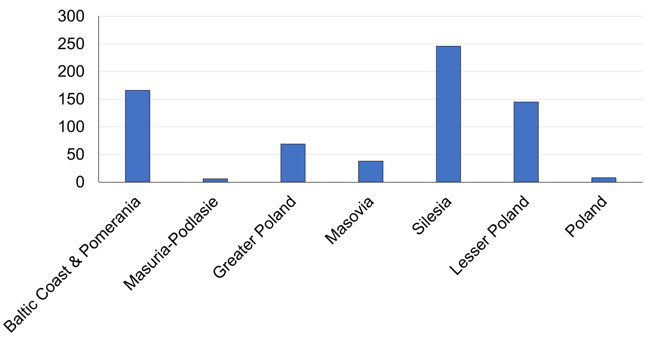

Fig. 3. Number of floods in Poland in the 17th–18th centuries in the six-main regions and miscellaneous category "Poland".

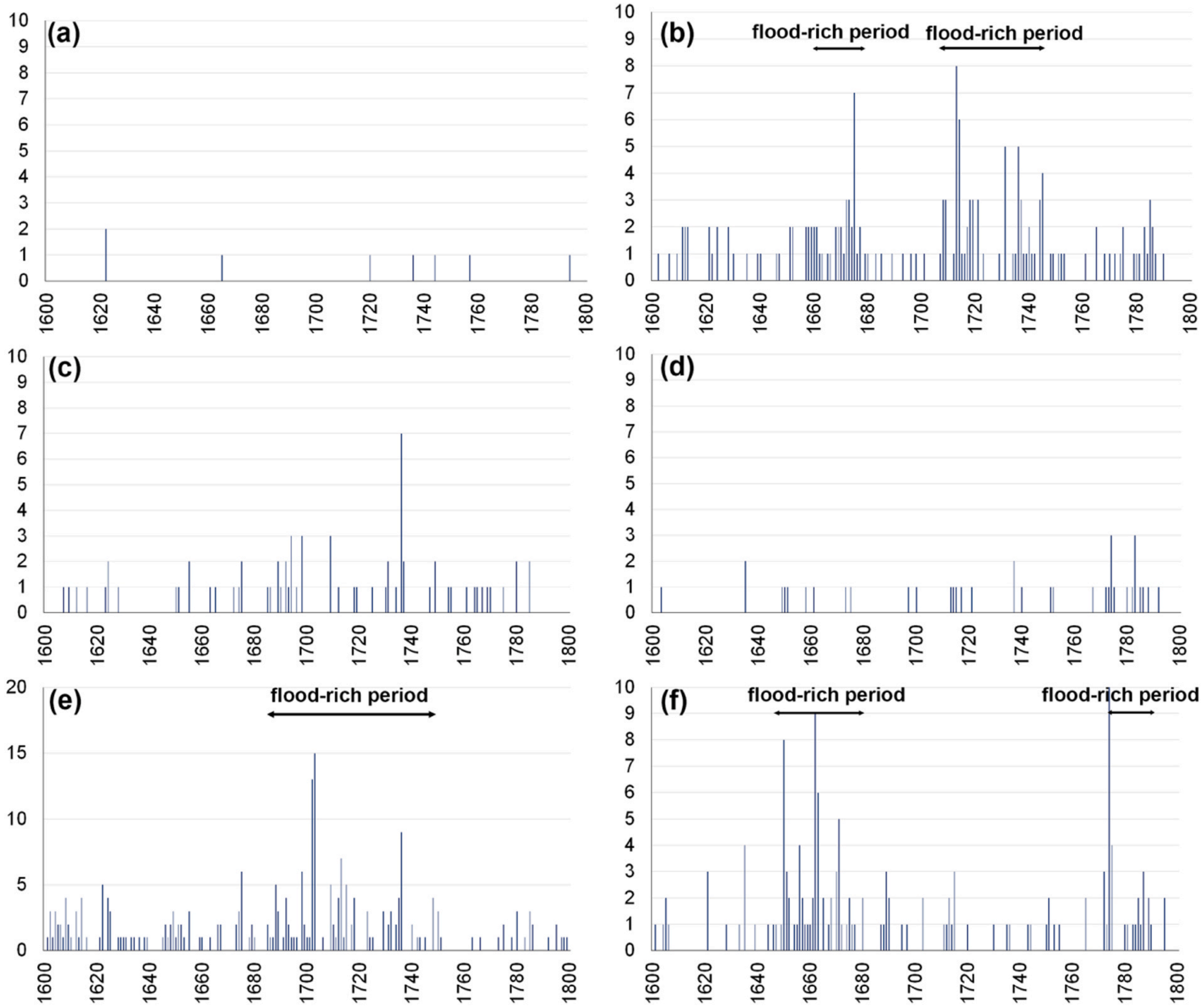

Fig. 4. Number of floods in the 17th–18th centuries, (a) miscellaneous category “Poland” (b) Baltic Coast and Pomerania, (c) Greater Poland, (d) Masovia, (e) Silesia and (f) Lesser Poland. Note: Due to the small number of floods in Masuria-Podlasie region, this region not shown (see Fig. 3).

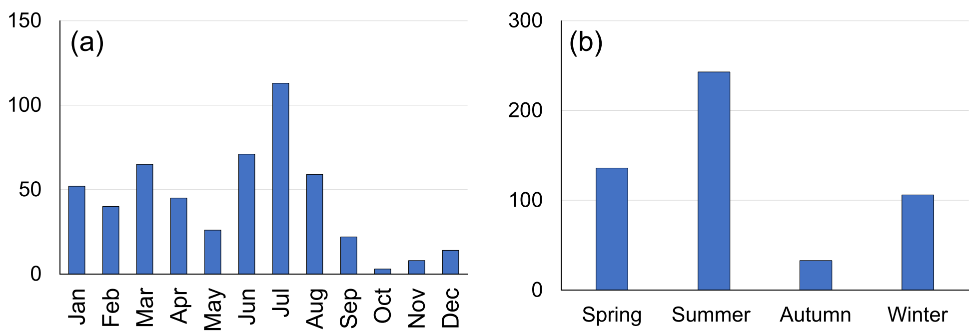

Fig. 5. Frequency of floods (a) by month and (b) by season.

used in our previous studies for historical floods in Poland (Ghazi et al., 2023a, b).

To assess the results in detail, we compared findings of this study with available studies for historical floods in Poland (Table 1). Among all the available studies, only Grześ (2008) provided a list of floods for Poland in the 10th–19th centuries. However, in his work, there is no detailed information about the intensity, origin or documentary references for these events. Majewski (1993) and Bielański (1997) provided information about historical floods in Poland for the Vistula Delta and Upper Vistula River, respectively. In

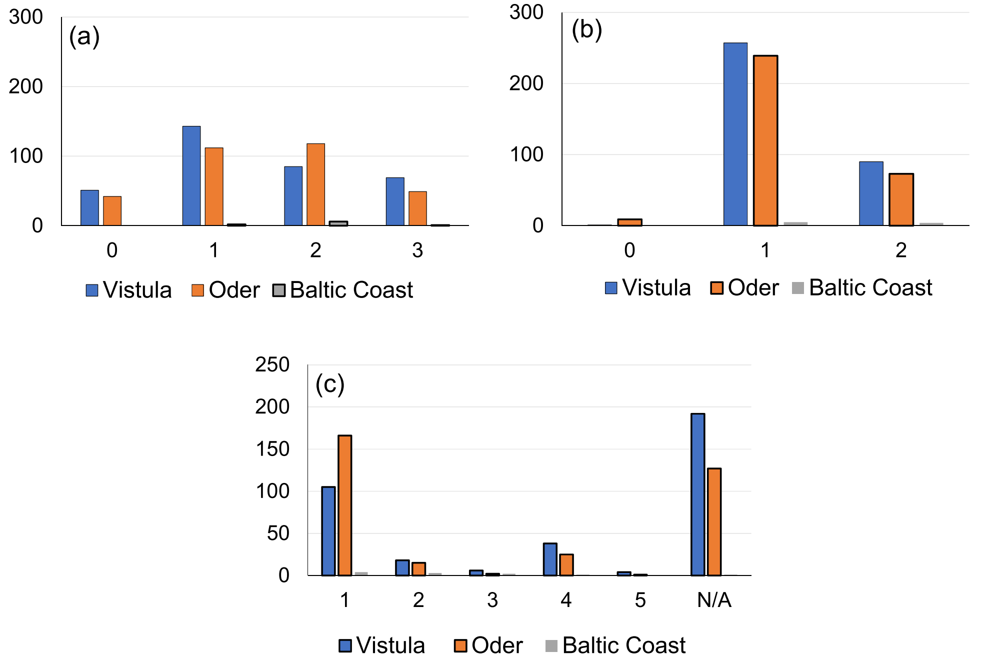

Fig. 6. Number of floods in Poland in period 1601–1800 based on the classifications of: (a) Brázdil et al. (2006b), (b) Barriendos and Coeur (2004), and (c) Lambor (1954), see Table S3 and S4 for classification details. Key: N/A – information not available.

addition, Mudelsee et al. (2003) studied flood occurrences in Central Europe, and Kasprzak (2010) investigated historical floods in the Oder River basin. We also extracted a list of floods for Poland based on a study analyzing floods in Europe in the last 500 years (Blöschl et al., 2020). Comparing the results of this study with the publications mentioned above showed that the number of recorded floods in this study (678 for all of Poland, 349 in Vistula River basin, and 321 in the Oder River basin) is significantly higher than those given by Grześ (2008) (70), Majewski (1993) (45), Bielański (1997) (14), Mudelsee et al. (2003) (71), Kasprzak (2010) (39) and (Blöschl et al., 2020) (74) (Table 1). In the comparison of flood occurrences, one flood in 1664 in the Mudelsee et al. (2003) source was classified as a high water in our database (see Table S6).

In addition, we compared the frequency of floods in the 17th–18th centuries in Poland with available sources (Glaser and Stangl, 2003; Mudelsee et al., 2003, 2006; Brázdil et al., 2005a, 2011; Brázdil and Kirchner, 2007; Rohr, 2007; Hohensinner, 2015; Retsö, 2015; Blöschl et al., 2020) from neighboring countries (i.e., Austria, Czech Republic, Germany and Sweden) (Table S7)) to provide an estimation for flood frequency in Europe during the 17th–18th centuries. However, the reader should be aware of possible biases related to differences between these countries in terms of the availability of detailed information allowing for the reconstruction of floods in rivers (including the number of rivers for which information exists). For example, we extracted data for flood occurrences for ten rivers in Germany, seven rivers in Czech Republic and significantly fewer for Sweden (4) and particularly for Austria (2) (see Table S7 for more details).

The results depicted in Fig. 7 show that the 20-year frequency of floods was greater in Poland and Germany than in other Central Europe countries. Only in two periods (1661–1680 and 1721–1740) was the number of floods higher in Poland than in Germany. This

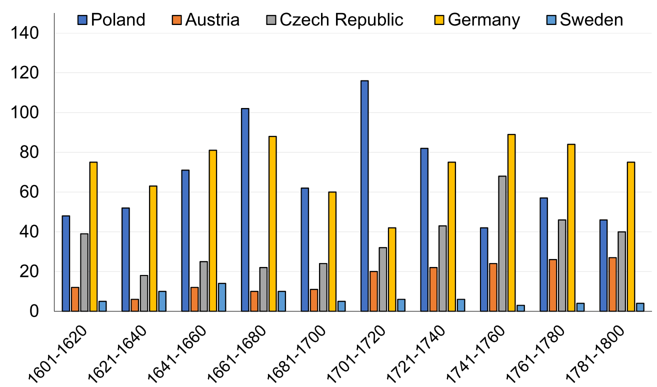

Fig. 7. Frequency of floods in the 17th–18th centuries in Central Europe.

is partly related to the differences in the numbers of rivers and areas of the countries, as well as to differences in availability of sources. Statistical evaluations demonstrated that ~63 % of floods in Germany and 35 % in the Czech Republic were also observed in Poland. The corresponding figures for Sweden and Austria were lower, standing at 19 % and 7 %, respectively. This is related to the number of sources available or used for the reconstruction of historical floods in these countries. In addition, the evidently smaller number of historical floods in Sweden than in other Central European countries also can be partly related to Sweden's climate, which is influenced by the presence of the Scandinavian mountains (rain shadow).

To obtain a more reliable comparison between floods occurring on the Vistula and Oder rivers (Poland) and in the other analyzed countries, we chose eight rivers from Table S7 for which there exist great numbers of floods. The number of floods occurring in the 17th–18th centuries in all rivers is presented in Fig. 8. Analysis of results illustrated in Fig. 8 shows that the rivers most prone to floods in the study period in Central Europe were the Danube, Main and Vistula Rivers (140–160 floods), and those least vulnerable were the Oder and Vltava Rivers (~60). Quite a large number of floods (>120) also occurred in Elbe River. In Sweden (the Norrstrom River), floods were registered only 31 times, i.e. usually 2–5 times less frequently than in all Central European rivers.

The comparison of simultaneous occurrences of floods in the study rivers (Fig. 8) revealed that such cases were common. Almost half of them occurred in the Vistula and Danube (44 %), on the Vistula and the Elbe (40 %) and on Vistula and the Main (39 %). A significantly smaller correspondence in flood occurrences was noted between the Vistula and Norrström rivers (only 10 %). The simultaneous occurrence of floods on the Oder and other Central European and Swedish rivers revealed a slightly better correspondence than did the results presented for the Vistula. The agreement in timing of occurrence of floods reached 50 %, 48 % and 44 %, respectively, for the following pairs of rivers: Oder–Danube, Oder–Elbe and Oder–Main. This correspondence between floods occurring on Oder River and rivers in Czech Republic (the Dyje, Morava and Vltava) is clearly smaller and ranges from 18 % (Dyje) to 29 % (Morava).

In the last decade, two comprehensive studies have been published by Glaser et al. (2010) and Blöschl et al. (2020) summarizing knowledge about flood occurrences in Europe in the past 500 years, and these warrant discussion here. They discovered different numbers of flood-rich periods for Central Europe in 17–18th centuries, that only partly overlapped on other. Glaser et al. (2010) identified two such periods (1640–1700, and 1730–1790), while Blöschl et al. (2020) found only one (1750–1800). Our results for Poland (see Fig. 2a) reveal the existence of one flood-rich period (1650–1740), which is more consistent with the findings presented by Glaser et al. (2010). Also in most of the studied regions (Baltic Coast and Pomerania, Silesia, and Lesser Poland) we identified an increase in floods frequencies in this time (Fig. 4). Only in Lesser Poland was there another flood-rich period noted in years 1775–1790 (Fig. 4f), which is consistent with the flood-rich periods identified by Glaser et al. (2010) and Blöschl et al. (2020). On the other hand, a very good correspondence of results exists between the timings of flood occurrences within a year. Both Blöschl et al. (2020) and we in this study have documented that floods in Central Europe dominate in summer and are least frequent in autumn (compare Fig. 5 herein and Fig. 5 in Blöschl et al., 2020).

Due to their dire consequences, the assessment of extreme floods has been always considered of great importance for flood occurrence studies. Thus, we evaluated the occurrences of extreme floods in this study with extreme floods in studies available for Poland and some neighboring countries (Table S8). It is also important to mention that the criteria for classification of floods as "extreme flood" in this study could differ from those utilized in other studies. In the Polish literature, a list of extreme floods has been presented only by Kowalewski (2006). However, the number of extreme floods in that source is only seven, whereas, based on the Brázdil et al. (2006b) classification (category 3), we documented as many as 69, 49 and 1 such cases in Vistula River, Oder River and Baltic Coast rivers basins, respectively. Significantly greater number of extreme floods were also distinguished in Poland (90, 73 and 4 floods in the basins of Vistula River, Oder River and Baltic Coast rivers, respectively) when the criterion proposed by Barriendos and Coeur (2004) was used (category 2). The number of extreme floods in Germany was relatively high, with 85 floods in various river basins, while in the other analyzed countries (Czech Republic, Sweden and Austria) the figures were markedly lower (20, 8 and 1, respectively). The year with occurrences of extreme floods in Poland (this study) and in other countries are listed in Table S8.

In general, the analysis of spatial variability of flood occurrences showed that they were most numerous in the Silesia region of

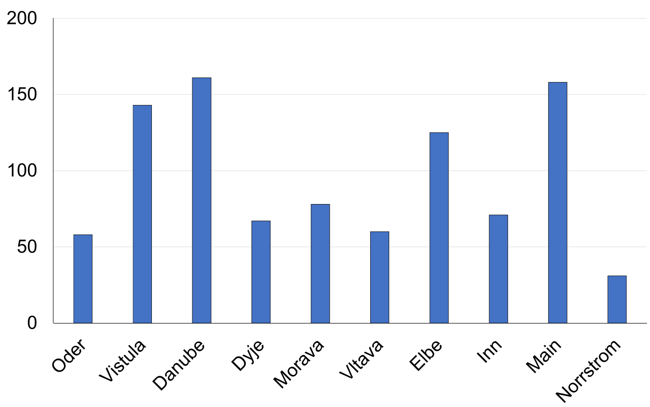

Fig. 8. Number of floods in main Central Europe rivers and in Sweden in the period 1601–1800.

south-western Poland (246, 36 %) and least numerous in the north-eastern Masuria-Podlasie region (6, less than 1 %). This discrepancy is partly related to the availability of sources and historical weather notes, which are evidently richer in the Silesia region than in the Masuria-Podlasie region. Furthermore, the Silesia region, particularly its Sudeten Mountains area, has a higher density of rivers compared to lowland areas, making it more vulnerable to extreme events than other regions in Poland.

The comparison of flood occurrences in Poland during the 17th–18th centuries against such statistics available for the medieval period (11th–15th centuries) (Ghazi et al., 2023a) and the 16th century (Ghazi et al., 2023b) revealed the existence of a rising trend. In general, the number of floods in the 17th–18th centuries (335 floods in the 17th century and 343 in the 18th) was slightly higher than in the 16th century (294 floods) and significantly higher than in the 11th–15th centuries (166 floods). This is partly related to the obvious increasing availability of historical sources and weather notes. The second possible reason is that, in the more distant past, there existed a tendency to describe mainly floods deemed to be truly extreme. Our calculations of the intensity of floods in Poland in the period 1001–1800 (this study and Ghazi et al., 2023a, b) based on the Brázdil et al. (2006b) classification support this opinion. We found that most of the floods in the 17th–18th centuries were of the category “smaller, regional floods”, whereas in the 11th–15th and 16th centuries the category “above average or supra-regional floods” was more common. Another important finding is that, except in the 16th century, floods were more common in the Vistula River basin than in the Oder River basin. The discrepancy, however, was significantly greater in medieval times than in the 17th–18th centuries. On the other hand, no changes throughout the time were noted in the origins of floods. In all three studied subperiods, rain and its subtypes were the main causes of flood in Poland.

It is worth mentioning that, despite the fact that hydraulic and hydrological designers use measurement data such as flow rate in the design of hydraulic structures, the findings of this study, by providing information from the history of floods in the study area, can provide useful information for the estimation of flood return periods.

5. Conclusions

The presented broad analysis of historical floods in Poland during the 17th–18th centuries based on documentary evidence improves our understanding of historical floods in Poland and Central Europe. To achieve this objective, a comprehensive database was constructed that included an indexing of each flood’s intensity and origin. It is worth noting that this study completed the knowledge gap for historical floods in Poland before the instrumental periods and will play a crucial role in bridging the knowledge gap for the assessment of historical floods in Europe before the 19th century. We would like to emphasize that in this study we tried to provide all available information for historical floods in Poland in the 17th–18th centuries from existing sources, and the findings provided in these results are based on all documentary evidence that has been made available to date. Thus, it is important to remember that the results for the frequency of floods may be modified and updated in the future if new sources come to light.

The primary findings and summary of this study are outlined as below:

1. Overall, 678 floods occurred in Poland in the 17th–18th centuries.
2. The frequency of floods in the Vistula River basin (51 %) is slightly higher than in the Oder River basin (47 %).
3. Floods occurred most in Silesia (246, 36 %), Baltic Coast and Pomerania (24 %) and Lesser Poland (21 %).
4. Floods mostly belong to the “smaller regional floods” category based on the Brázdil et al. (2006b) classification and the “extraordinary” category in the Barriendos and Coeur (2004) classification.
5. The greatest number of floods by season occurred in summer, of which, especially in July.
6. Rain and its subtypes were the dominant reason for flood occurrences.
7. Overall, in Poland, 119 “extreme floods” occurred based on the Brázdil et al. (2006b) classification (category 3) and 167 floods classified as “extreme floods” in the Barriendos and Coeur (2004) classification (category 2).
8. Comparison of the spatial coherency of floods in Poland with other Central Europe countries showed that there is a good coherency with floods occurring in Germany and Czech Republic.

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CRediT authorship contribution statement

Babak Ghazi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Rajmund Przybylak:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Funding acquisition, Project administration, Validation, Supervision, Writing – original draft, Writing – review & editing. **Piotr Oliński:** Investigation, Data curation, Validation. **Michał Targowski:** Data curation, Validation. **Janusz Filipiak:** Data curation, Validation. **Aleksandra Pospieszyńska:** Data curation, Validation, Software, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The dataset of flood records for Poland in the 17th–18th centuries is available at (https://doi.org/10.18150/VLPAFG). Other data used in this research are available from the corresponding author, upon reasonable request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101796.

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Flood occurrences and characteristics in Poland in the last millennium

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Abstract

Knowledge about the frequency, intensity, and genesis of floods during historical periods (before instrumental observations) in river basins worldwide is limited, mainly due to gaps in the coverage, quality, and range of the necessary information available in documentary evidence. Creating a comprehensive and reliable database is also time-consuming, and therefore the number of studies analyzing floods in different parts of the world is limited. Using all available quality-controlled documentary evidence, a new comprehensive database of flood occurrences in Poland in the 11^{th}–18^{th} centuries was created. In addition, a list of floods for the 19^{th} and 20^{th} centuries was created based on literature. Based on these data, the frequency, intensity, and genesis of floods in Poland in the last millennium were investigated. Analysis of both databases revealed the occurrence of 1,680 floods in Poland. The 18^{th} century was the most abundant in recorded floods (356, 21%), while 19^{th} century was least abundant (187, 11%). Floods in period 1001-1800 were most frequent in the Silesia region (553, 43%) and in the Oder River basin (671, 55%). The number of floods was greatest in summer (JJA, 46%), and the lowest in autumn (SON, 8%). Investigation of the origin of floods indicated that rain was the main contributing factor to occurrences of floods in Poland (44%). The estimation of the intensity of floods showed that most of them were of extreme nature: "above-average, or supra-regional flood" (33%) and "extraordinary" floods (70%) based on Brázdil et al. (2006) and Barriendos & Coeur (2004) classifications, respectively. The Mann–Kendall (MK) statistical trend results showed that, in the period 1501–2000, there was a statistically significant decreasing trend (p-value < 0.05) in the frequency of floods in Poland. On the other hand, in the sub-periods 1501–1800 and 1801–2000, the trends were positive, though they were statistically significant only in the latter period.

Keywords: Historical floods; Historical hydrology; Historical climatology; Historical Poland; Central Europe; Last millennium; Documentary evidence

Introduction

Floods are one of the most common weather-related natural hazards, causing devastating impacts worldwide. The impacts of floods are expected to increase by the end of the 21st century due to climate change, population increases, and economic growth (Tanoue et al., 2016). In recent years and decades, Europe has experienced several devastating floods, with various social and economic damages (CRED, 2015). For example, such catastrophic floods occurred: (i) in 1997 in the Oder River (Mudelsee et al., 2004); (ii) in 2010 in Poland, Austria, Czechia, Hungary, Slovakia, and Serbia (Bryndal, 2015); (iii) in 2013 in the Danube River (Blöschl et al., 2013); and (iv) in the summer of 2021, in Germany, Belgium, and the Netherlands (Lehmkuhl et al., 2022; Mohr et al., 2022). The European Environment Agency has estimated more than 12 billion euros in economic losses per year due to flood-related phenomena (Feyen et al., 2020). Thus, due to the inherently involved adverse consequences of floods to society and the environment, the assessment of flood events remains an important task for the scientific community.

The analysis of long-term flood frequency and intensity can provide a clear insight into this complex phenomenon. The main limitation in completing this task is the lack of detailed investigations for flood variations over time, especially before the instrumental period, including in Poland. To improve knowledge for the area of Poland, a new comprehensive database of floods in Poland in 1001–1800 was created (for details, see Ghazi et al., 2023a; Ghazi et al., 2023b; Ghazi et al., 2024). Based on this database, separately for the 11th–15th, 16th, and 17th–18th centuries, some results have been already published in the cited papers. For the present research, we additionally created a list of floods for 19th–20th centuries using information available in the literature. Many aspects of flood occurrences in the area of Poland in the entire last millennium have not previously been comprehensively investigated, in particular those regarding time and spatial changes in frequency, intensity, and origin. Therefore, the main objective of this research is a deep investigation of those issues in Poland in the study period using all available information gathered in the mentioned database. Our aim is also to investigate all possible characteristics of floods separately for the pre-instrumental period (1001–1800) and the instrumental/industrial period (1801–2000) to estimate similarities and/or differences between them. Literature reviews of historical floods in Poland have been deeply investigated in our previous studies (Ghazi et al., 2023a; Ghazi et al., 2023b). The outputs of this study presents a comprehensive picture for historical hydrology and climatology studies in Central Europe and complete the knowledge gap for historical flood studies in Poland.

Study area

Poland is located in the Central Europe between the Baltic Sea in the north and the Sudetes and Carpathians in the south. Poland's borders have changed numerous times throughout history and its borders were completely different from the current boundary of Poland (See Fig. S1). To conduct this research, we used the current boundary of Poland which is divided into the regions of Baltic Coast and Pomerania, Greater Poland, Lesser Poland, Masuria-Podlasie, Masovia, and Silesia (Fig. 1). There are three main river basins in Poland (Baltic Coast, Vistula, and Oder rivers basins). In the database of floods in Poland in the 11th–18th centuries, all flood records were identified to one of the mentioned regions and river basins. In some cases, however, information about a flood was too general and thus not precise enough to identify the exact region of its occurrence. Thus, for these flood events, we defined a separate category called "Poland".

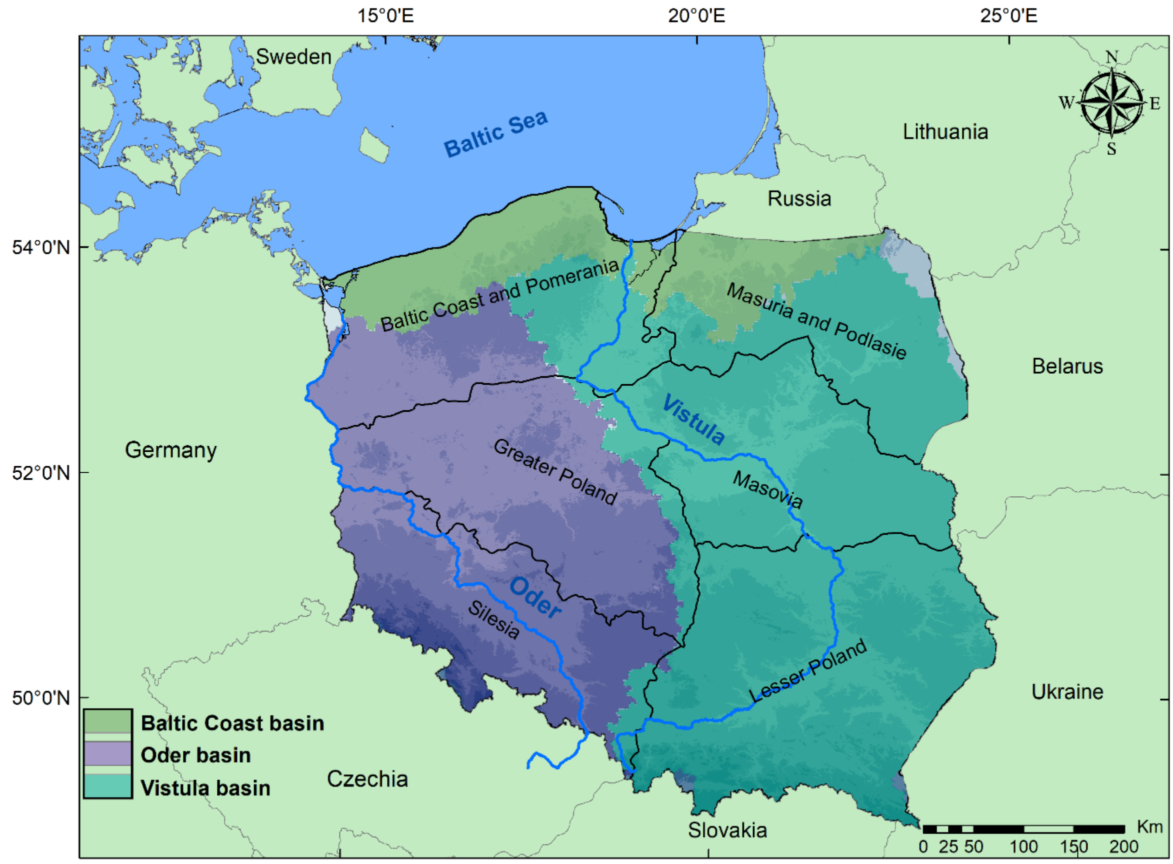

Fig. 1. Geographical location of Poland, main regions and river basins

Data and methods

To conduct this research, we used a database of historical floods in Poland in the 11th–18th centuries (https://doi.org/10.18150/VLTVD9). This database was created based on various documentary sources such as handwritten and unpublished sources, published sources and so called "secondary literature" (See Table S1). The total number of them reached 563 items (Fig. 2). It is well seen that, for medieval times, the sources were very limited (only 114). On average, their number per century was about 5–7 times smaller during the medieval period than in the other three analyzed centuries (16th–18th centuries), when the number of sources was more or less stable, in particular in the 17th and 18th centuries.

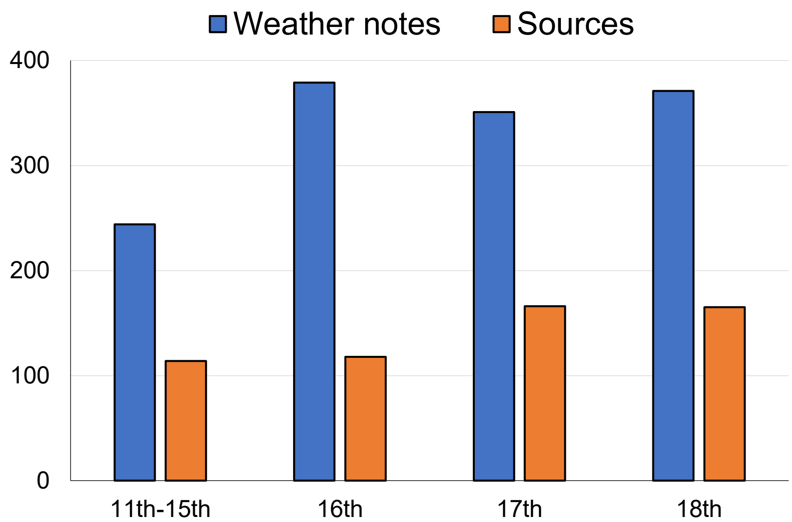

Fig. 2. Number of used weather notes and sources to identified floods in Poland in the period 1001–1800

Floods in Poland, similarly as in majority of other countries, are the most common natural disaster event mentioned in historical sources. Among the various sources, narrative sources are the most useful and important. Due to the negative consequences of floods, these events were very often described in chronicles of cities, monasteries, parishes, families, and others. The descriptions of events are sometimes quite comprehensive and provide many details about the occurrences and their characteristics. Nevertheless, for some events, even in cases of severe floods, the yearbooks (Annales) provided only a short description. Other good sources containing information about floods are memoirs, travel diaries, and private correspondence. In the 18th century, the importance of newspapers as a source of knowledge about floods also grew. Useful information about floods is also available in some administrative sources. For example, floods are mentioned in the minutes of city council meetings and meetings of estates in some provinces of the Polish state (especially the meeting minutes of Prussian estates in Royal Prussia). Other good examples are accounting sources that provide information on expenses for repairing damage after floods. Municipal and land records contain information about exemptions from various obligations for peasants who suffered from floods. Finally, many accidental entries are placed in the margins of multiple books that inform people about floods. Much information about floods from the Middle Ages to the end of the 18th century is also found in later literature (dated from the 18th to 20th centuries), especially in monographs of individual regions and cities. This is often the only preserved information about flood events, as many old sources were destroyed during the numerous wars that have occurred in the history of Poland.

To assess flood occurrences in Poland in the 11th–18th centuries, we used 1,345 weather notes (see Table S2 and Fig. 2). Similarly as for sources, the number of them is small before 1500, and later on is stable and ranges from 351 (17th century) to 379 (16th century). In addition, in the database, the flood intensities were classified based on Brázdil et al. (2006) and Barriendos and Coeur (2004), and the origins of floods were classified according to the method of Lambor (1954) (See Table S3–S4). The detailed information regarding the procedure of creating the database is available in our previous studies (Ghazi et al., 2023a; Ghazi et al., 2023b). In the database of floods, for the category of "Poland" when there is no detailed information about place, regions or river name(s), no information about river basins is provided. In addition, if in the weather notes there is clear information about flood ocurrences in two rivers, we assumed them to be two different independent floods, whereas when there is information that flood occurred in two rivers which are close to one another, (e.g., near the mouth of a smaller river into a larger one) we assumed that to be one flood. It is worth noting that in some cases, the weather notes contain only information about rivers, so in the database we added only the river name in the column describing the place. Also, for floods for which the place is specified in the record but the river name is not, we listed the river as the main river of the basin in which the specified place is at present located.

In the classification of flood intensity, to distinguish "floods" from "high-water", an event was considered as a flood if it met the Barriendos & Coeur (2004) classification as category "0" (ordinary flood).

The information about flood occurrences in Poland in the 19th–20th was gathered based on available contemporary publications (Majewski, 1993; Bielański, 1997; Mudelsee et al., 2003; Grześ, 2008; Kasprzak, 2010; Blöschl et al., 2020). In the assessment of flood occurrences, for comparison purposes, we use sub-periods (i.e., medieval period (11th–15th centuries) and, separately, the 16th, 17th, 18th, 19th and 20th centuries).

In order to evaluate the possible changes in the frequency of historical floods, the trends and their statistical significance were analyzed using Mann–Kendall (MK) tests (Mann, 1945; Kendall, 1948). The MK test is a non-parametric test widely used to detect changes in hydrological and climatological time series. To avoid uncertainty of trends for missing value(s), we applied the MK test for decadal frequencies of flood. The capability of MK test in analyzing trends of flood frequency has been approved in previous studies (Mangini et al., 2018; Blöschl et al., 2019; Venegas-Cordero et al., 2022). The assessment of MK test is carried out from the following equation:

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} \mathrm{sign}(x_i - x_k),$$

$$\text{where sign } (x_i - x_k) = \begin{cases} +1 & \text{if } (x_i - x_k) > 0 \\ 0 & \text{if } (x_i - x_k) = 0 \\ -1 & \text{if } (x_i - x_k) < 0 \end{cases}$$

In this formula, x_i and x_k represent values sorted by sequence of data, and n represents the length of the dataset. The positive (negative) value of S indicates that the series is increasing (decreasing) over time. In the MK test, a significance level (alpha) (e.g., 0.05) is calculated to determine the threshold for statistical significance. Also, a p-value is calculated that expresses the probability that the test statistic is as extreme as the observed one assuming that the null hypothesis is true. In general, the p-value below a significance level (alpha) ($p<\alpha$), indicate that there is a significant trend in the data series. If the p-value is equal or greater than alpha ($p\geq\alpha$), it means that there are no significant trends for dataset.

Results

The analysis of the documentary evidence yielded records relating to 1,252 floods in Poland in the 11th–18th centuries (Fig. 3a). They were less frequently recorded in the medieval times (210) mainly due to evidently smaller number of available historical sources (see Fig. 2). In particular, a small number of floods was noted before the 14th century (20). Better availability of historical sources for Poland is seen in the 15th century, in particular in its second half. As a result, more information about floods is also available. From the 16th century until the 18th century, the century frequencies of floods were comparable (345, 341, and 356 floods). It is a little surprising that the numbers of floods in Poland in the 19th and 20th centuries were smaller than in the previous three centuries and reached 187, and 241, respectively. One of the reasons for this may be connected with the differences in the methodologies that different authors use for distinguishing floods.

By distinguishing flood occurrences in main river basins (see Fig. 3 and Fig. S2) in the period 1001–1800, it was revealed that the number of floods on the Oder River (671) was slightly higher than in Vistula River basin (522 floods). The number of floods in the basins of Baltic Coast rivers (31 floods) was significantly lower than those for the Oder and Vistula basins.

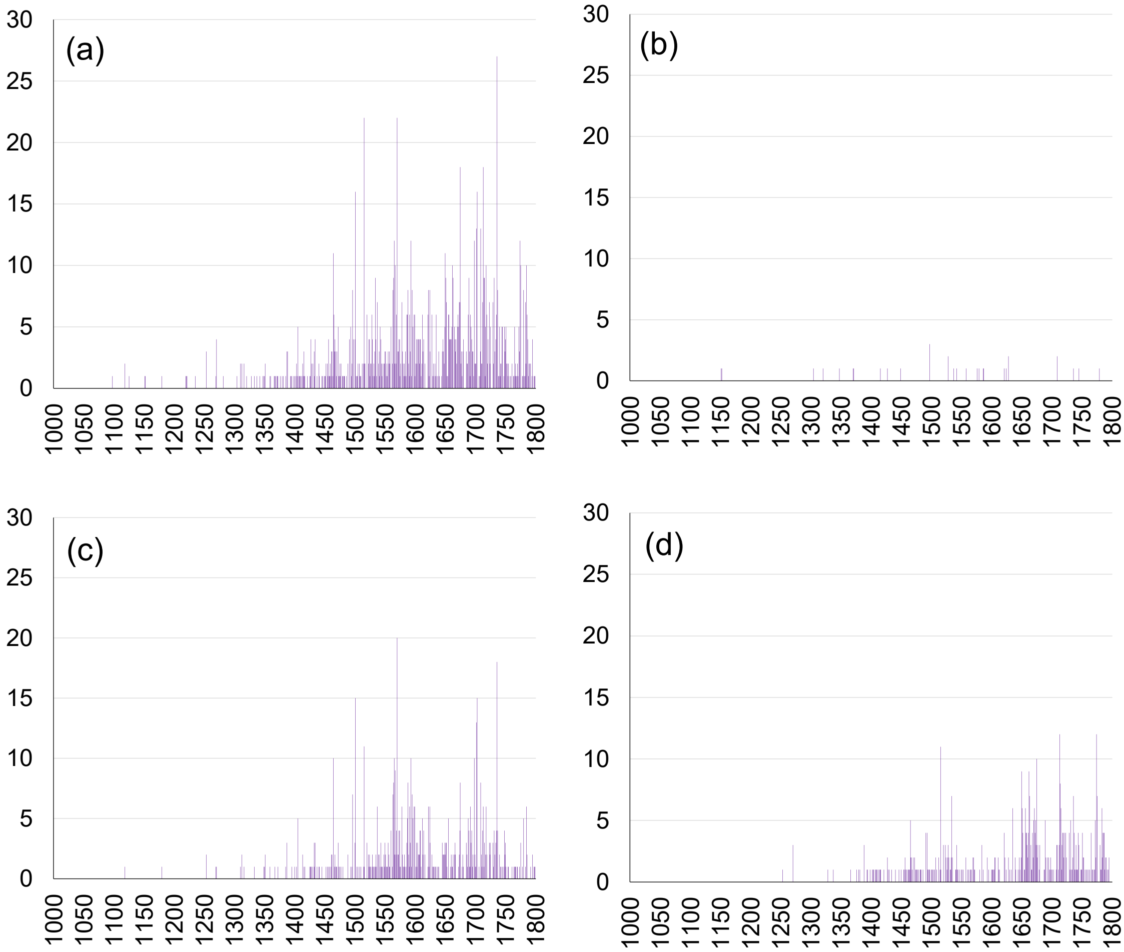

Fig. 3. Number of floods in main river basins in Poland, AD 1001–1800: (a) All river basins in Poland, (b) Baltic Coast rivers basin (c) Vistula River basin, and (d) Oder River basin

Assessment of history of floods in river basins according to different centuries demonstrated that the highest per-century number of floods in Poland occurred in the 18th century (354) (see Fig. 4 and Fig. S2). In Baltic Coast rivers basin, flood occurrences are recorded most numerously for the 11th–15th centuries (13), while only four were noted in the 17th century. In the Vistula River basin, the per-century number of floods was highest (187) for the 18th century and lowest for the 20th century (69). The highest and lowest numbers of flood records for the Oder River basin occurred in the 16th (245) and 11th–15th (96) centuries.

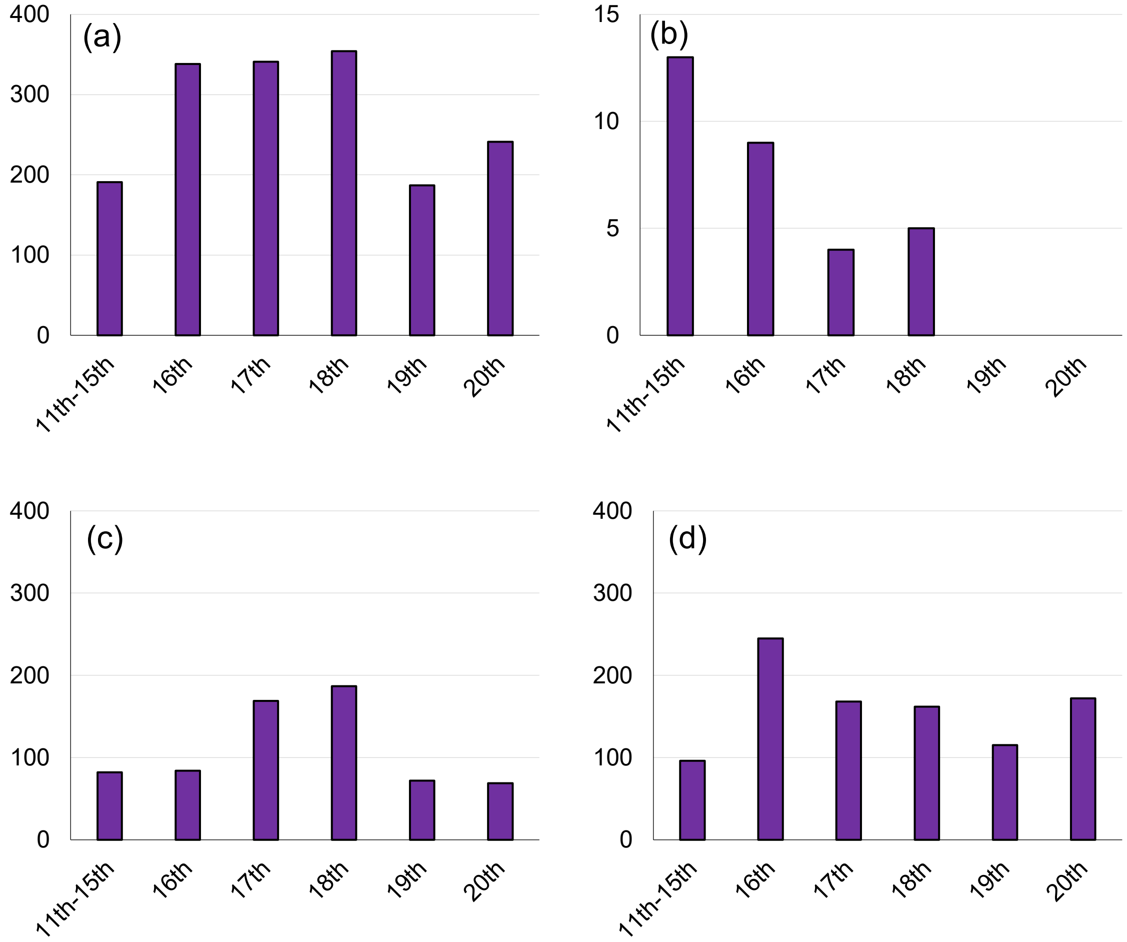

Fig. 4. Number of floods in main river basins in Poland in different centuries, 1001–1800. (a) all river basins, (b) Baltic Coast rivers* basin (c) Vistula River basin, and (d) Oder River basin

* Key: there is no record for floods in the 19th and 20th centuries for this area; please note the scale difference in Fig. (b)

The spatial distribution of floods in Poland in the 11th–18th centuries is presented for six main regions (see Fig. 5 and Fig. S3). The results show that floods were most common in Silesia region (553 cases). Relatively high numbers (289 and 212) were also noted for the Baltic Coast and Pomerania region and the Lesser Poland region, respectively. The frequencies of floods in the Masuria-Podlasie, Greater Poland, and Masovia regions were significantly lower, at 11, 109, and 53, respectively. In addition, as many as 46 floods were attributed to the category "Poland" because the detailed place of occurrence is unknown.

In most regions (Baltic Coast and Pomerania, Masuria-Podlasie, Greater Poland, and Masovia), the number of floods was highest (101, 4, 40, and 30, respectively) in the 18th century (Fig. 6). In the other two regions, floods were clearly most frequent in the 16th century for Silesia (211 cases) and in the 17th century for Lesser Poland (90 cases). The lowest numbers of floods occurred in the 11th–15th centuries or in the 16th century (see Fig. 6).

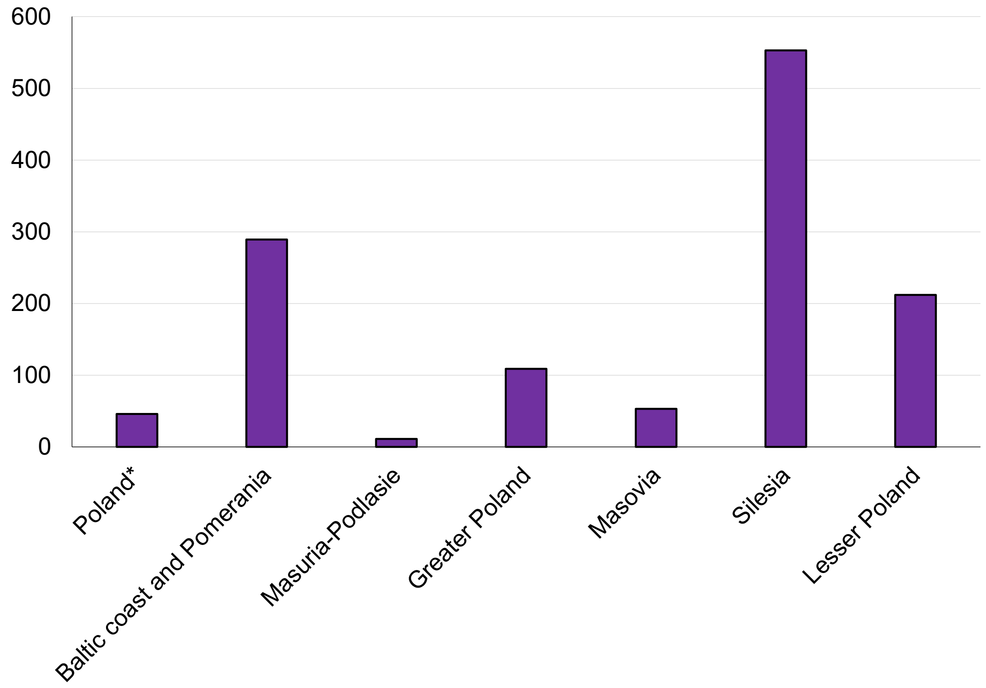

Fig. 5. Number of floods in main regions of Poland, AD 1001–1800
*Key: category “Poland” with no detail for geographical location of floods

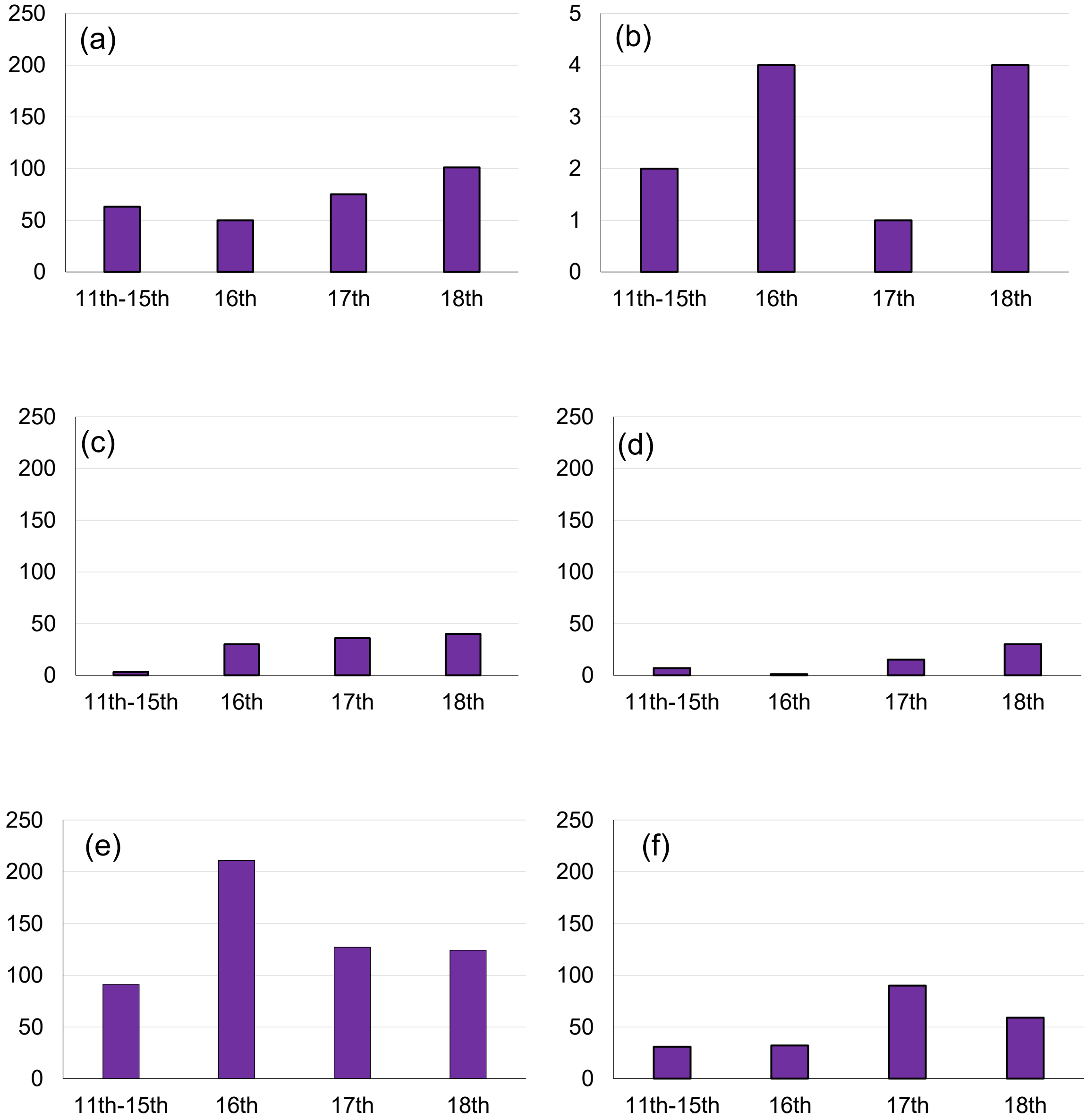

Fig. 6. Number of floods in different regions in Poland in different centuries, 1001–1800. (a) Baltic Coast and Pomerania, (b) Masuria-Podlasie, (c) Greater Poland, (d) Masovia, (e) Silesia, (f) Lesser Poland; please note the scale difference in Fig. (b)

The analysis of the monthly frequency of floods in Poland in the period 1001–1800 (see Fig. 7a and Fig S4a) showed that the highest number of floods occurred in July (159), August (117), and June (109), while much the lowest numbers occurred in December (23), October (16) and November (12). The investigation of seasonal frequency of floods demonstrated that 46% of floods occurred in summer and 27% in the spring (Fig. 7b and Fig. S4b). The lowest frequencies of floods were noted in the autumn and winter (8% and 18%, respectively). This seasonal pattern in flood occurrences in Poland is also observed in each of the sub-periods (see

Fig. S5). In terms of the seasonal frequency of floods by region (see Fig S4b), the highest number of floods in the Baltic Coast and Pomerania (42%) and Greater Poland (43%) occurred in the spring, while for the Masuria-Podlasie (66%), Masovia (40%), Silesia (59%), and Lesser Poland (62%) the summer was the main season for flood occurrences.

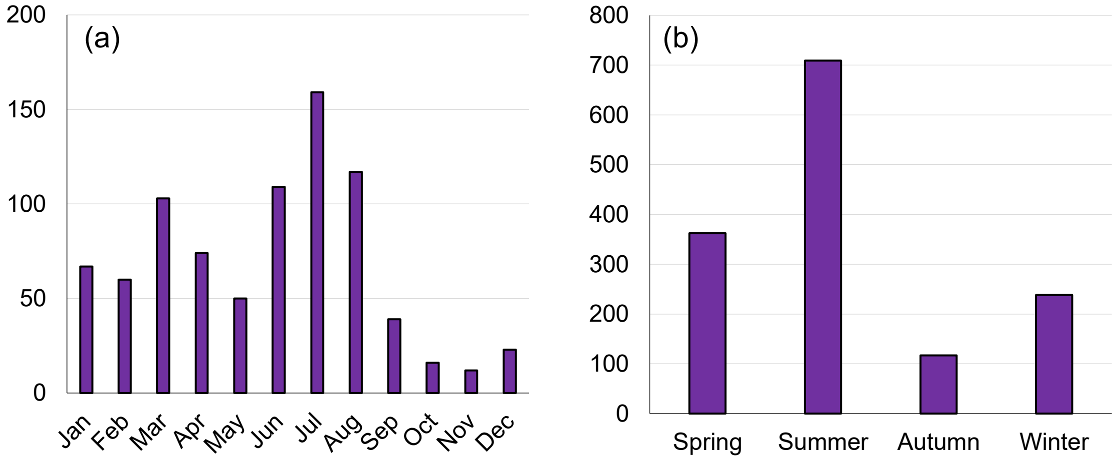

Fig. 7. (a) Monthly and (b) seasonal floods frequencies in Poland in 11th–18th centuries

Results describing flood intensities and origins according to the criteria proposed in the paper are shown in Table S5 and Figs 8 and 9. As it is seen from Fig. 8, the flood intensities in Poland in the 11th–18th centuries were estimated according to four grades/categories (0-3) using the Brázdil et al. (2006) classification and three grades/categories (0-2) using the Barriendos and Coeur (2004) classification (for more details see Table S3). According to the first classification most numerous were floods classified as category "2" ("above-average, or supra-regional flood", 408 cases) and "1" ("smaller, regional flood", 403) (Fig. 8) According to the second classification's proposition the category "1" ("extraordinary") was most frequent. The second most frequent group of floods was attributed to the category "2" ("catastrophic"), but their frequency was about two times smaller than the category "1". The third category of floods distinguished by Barriendos and Coeur (2004), which they called "ordinary" (category "0"), was not classified by us as flood but as a "high water" level state. In the study period we found 62 such cases in Poland. Most of them were recorded in the Silesia region (48) and Oder River basin (see Table S6).

Estimation of flood origins based on the Lambor (1954) classification demonstrated that most floods (553) in the study period in Poland were caused by rain. Relatively small numbers of them (77, 62, 23, and 7) were caused by winter-related phenomena (ice jam or shuga), snowmelt, storm, and anthropogenic reasons, respectively. Assessment of flood origins by region (Fig. 9) also shows the dominance of rain in this process.

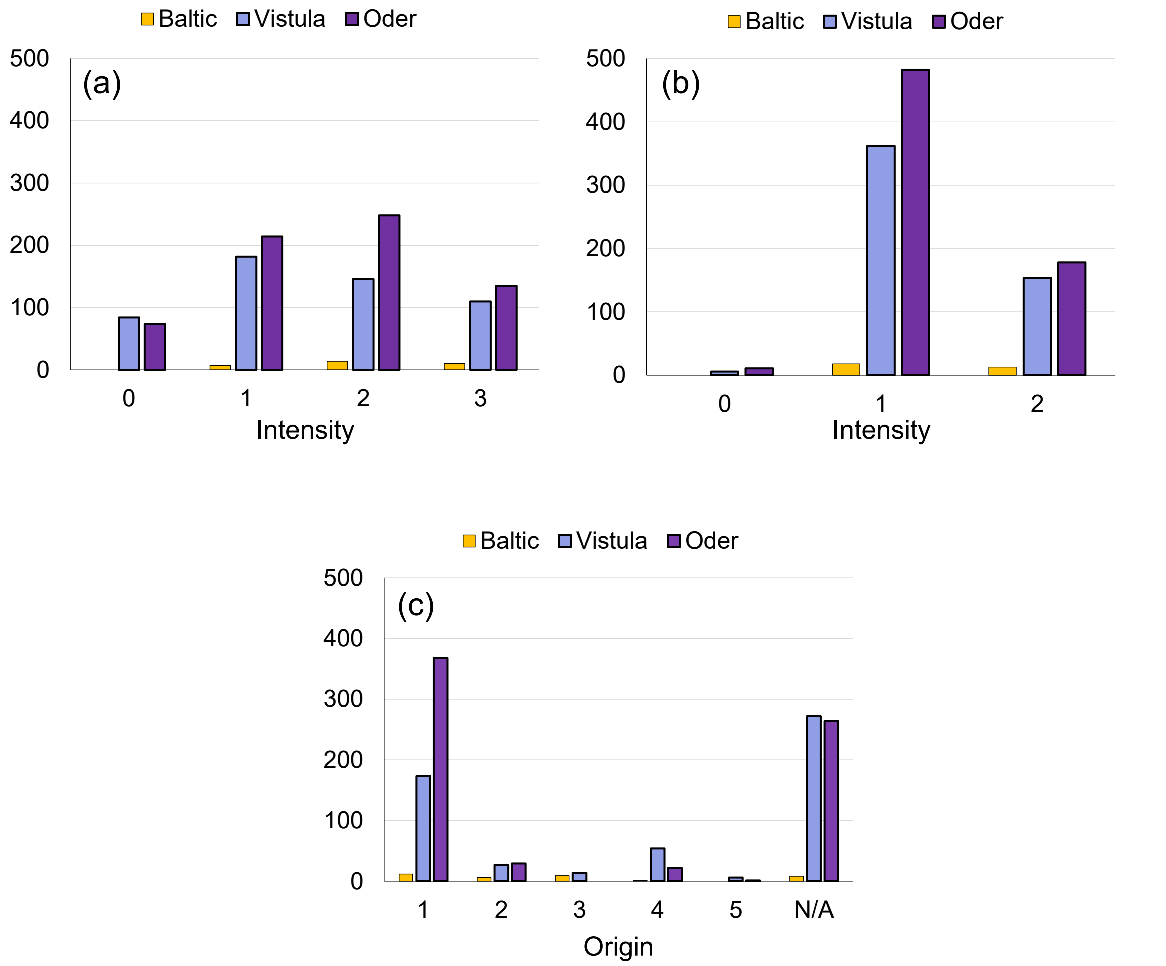

Fig. 8. Number of floods in main river basins of Poland in the 11th–18th centuries based on (a) Brázdil et al. (2006), (b), Barriendos and Coeur (2004) intensity classification and (c) Lambor (1954) origin classification

The flood intensity evaluation shown for the six major regions (Fig. S6) demonstrated that, based on the Brázdil et al. (2006) classification, floods attributed to the category "2" ("above-average, or supra-regional flood") were most frequent in the Silesia (212 cases) and Masuria-Podlasie (4). On the other hand, the category "1" ("smaller, regional flood") dominated in the Baltic Coast and Pomerania (104), Greater Poland (53), Masovia (15), and Lesser Poland (68) regions. Estimation of flood intensity based on the Barriendos and Coeur (2004) classification revealed that category "1" ("extraordinary") is most common in every region.

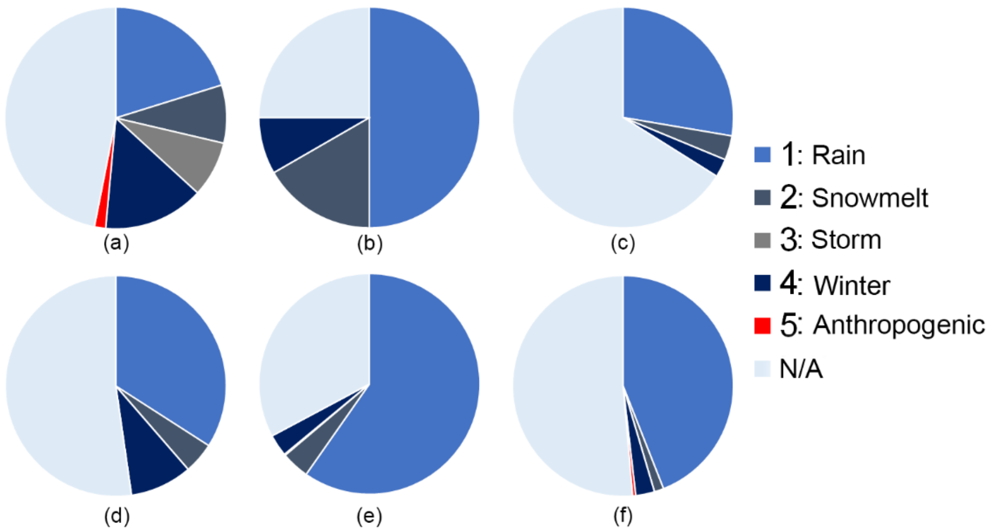

Fig. 9. Classification of origin of floods in Poland in the 11th–18th centuries based on Lambor (1954) for (a) Baltic Coast and Pomerania, (b) Masuria-Podlasie, (c) Greater Poland, (d) Masovia, (e) Silesia, (f) Lesser Poland

The investigation of time changes in the share (%) of extreme floods relative to all distinguished floods in Poland in the study period is illustrated in Fig. 10. In general, in line with expectation the share decreases with time, which supports the opinion commonly expressed by historians that chroniclers of the more distant past had a greater tendency to focus on very extreme events than did later chroniclers. For example, analysis of the category "2" floods in Barriendos and Coeur (2004) classification revealed that their relative frequency was highest (41%) in the 11th–15th centuries, and only a little over half that in the 18th century (22%). The same trend in ratio of extreme floods to all floods, though weaker, is also noted in category "3" of floods according to the Brázdil et al. (2006) classification.

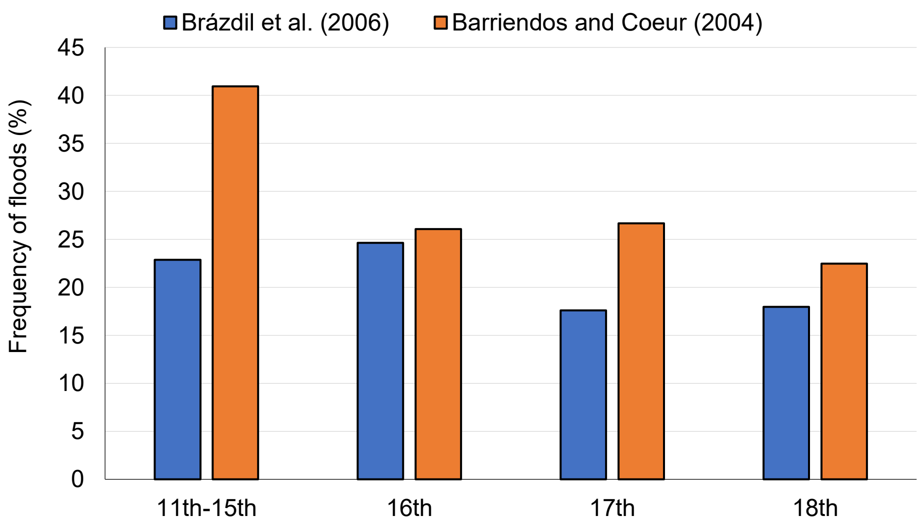

Fig. 10. Percentage share of extreme floods ("category 3" as per Brázdil et al., 2006, and "category 2" as per Barriendos and Coeur, 2004) in all floods distinguished for Poland in the study sub-periods

Assessment of the origin of floods based on the Lambor (1954) classification by century is depicted in Fig. 11. Results indicated that for category 1 (“rain and it subtypes”), the relative frequency of floods caused by rain (among those floods for which the cause is known) was highest in the 16th century (53%) and lowest in the 18th century (37%). For category 2 (“snowmelt”), the number of floods was highest in the 18th century (7%) and lowest in the 17th century (2%). Category 3 floods (“storm”) were at their most common in the medieval period, whereas category 4 floods (“winter”-related) were at their most common in the 18th century. Category 5 floods (“anthropogenic”) and the “N/A” category were at their most common in the 17th century. The relative frequency of the “N/A” category of floods (those lacking information about the cause) changes little in time and oscillates in the range 35–45% for the analyzed sub-periods (Fig. 11b).

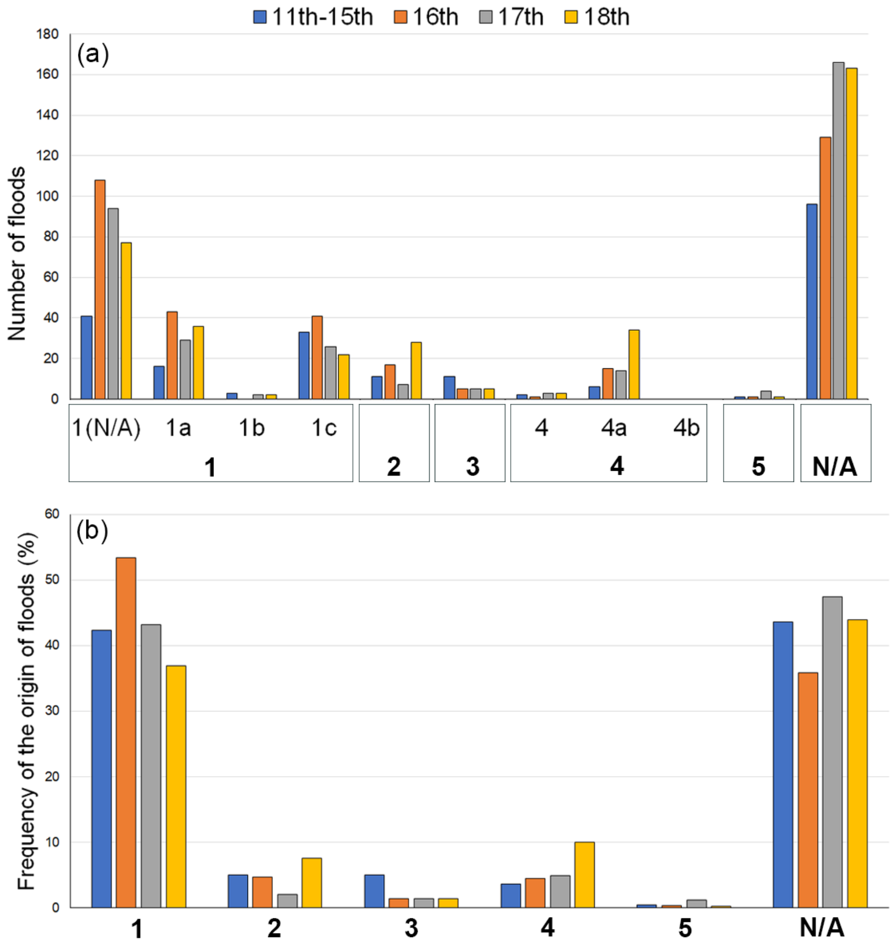

Fig. 11. Frequency of type of origin of floods in Poland in period 1001–1800 (a) number of floods and (b) relative frequency based on Lambor (1954) classification
(For symbols explanation, see text and Table S4)

Since rain was the main cause of floods for the study area, we also evaluated changes in seasonal flood occurrences for its different categories (including subtypes) (see Fig. S7). It is clear that the historical sources for most floods indicated rain as their main cause, but it was not possible to clearly indicate its subtype. The category we defined as "rain (N/A)" is the predominant category on average in all seasons (from 63% in autumn, 58% in summer, 48% in spring, to 44% in winter), although not in all analyzed 50-year periods. For the rest of the floods, a more detail cause could be indicated: torrential rain (category 1a), frontal rain (1b) or long-lasting rain (1c). In all seasons, two categories clearly dominated, i.e. 1a and 1c (Fig. S7). The most common causes of floods were torrential rains in spring (28%) and summer (20%) and long-lasting rains in winter (24%) and autumn (23%).

Another result that we present here is the geographical location of floods that occurred in Poland in the 11^{th}–18^{th} centuries (see Fig. 12). Analysis of this figure shows that the spatial density of flood occurrences in Poland was greatest in three general areas: south-western and south-eastern Poland, and the middle of northern Poland (of which, especially the area of the Lower Vistula river). Secondary density of floods was noted in the middle of both the western and eastern parts of Poland. The highest number of floods (>10) in the study period occurred at the following sites (towns): Wrocław (72), Boleslawiec (59), Gdańsk (52), Kraków (50), Poznań (50), Nysa (34), Toruń (31), Malbork (30), Żytawa (29), Krosno Odrzańskie (25), Mirsk (25), Gubin (24), Warszawa (23), Zgorzelec (23), Kłodzko (22), Gorzów Wielkopolski (20), Złotoryja (18), Pilzno (17), Racibórz (15), Brzeg (14), Gryfów Śląski (14), Legnica (14), Świdwin (12), Forst and surroundings (11), Lwóewek Śląski (11), Słońsk (11), and Szczecin (11).

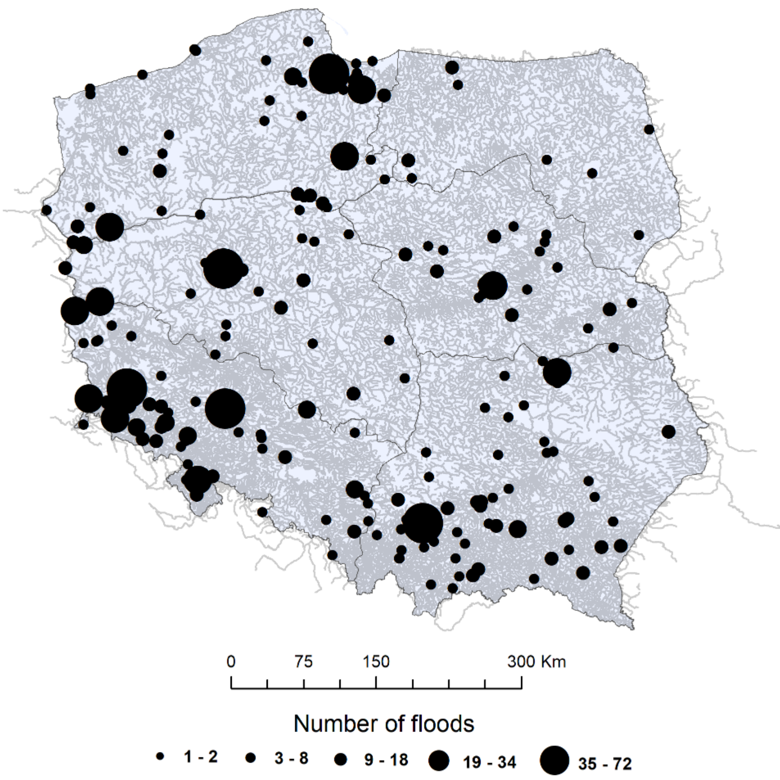

Fig. 12. Geographical location of flood occurrences in Poland in the period 1001–1800

The issue of time-dependent changes in flood frequencies is now, in the era of global warming, a crucial topic of research. Having at our disposal a comprehensive and complete database of floods for Poland, we present changes in decadal frequencies of floods in the last millennium (Fig. 13). It is obvious that trends (especially long-term trends encompassing centuries) can be calculated to only a fairly low degree of certainty for medieval times, due to the limited and uneven access to sources for that period. That is why we did not calculate linear trends for this time period. Since the 16th century, however, there have been no such obstacles, because the number of both historical sources and weather notes used are comparable for all analyzed centuries (see Fig. 2). Therefore, we present flood frequency trends based on decadal totals for three periods: 1501–2000, 1501–1800, and 1801–2000 (Fig. 13). The three-decadal moving average of flood frequencies is shown for the entire period to describe the general tendencies in shorter time periods (of about 30 years). However, again, trends for medieval times are subject to a large uncertainty error. Based on MK test evaluation, the results demonstrated that for the periods of 1501–2000 and 1801–2000 there are statistically significant trends (p-value < 0.05), while there was no statistically significant trend for 1501–1800 period. Also, results indicated decreasing trend for 1501–2000, but increasing trend for the last 200 years.

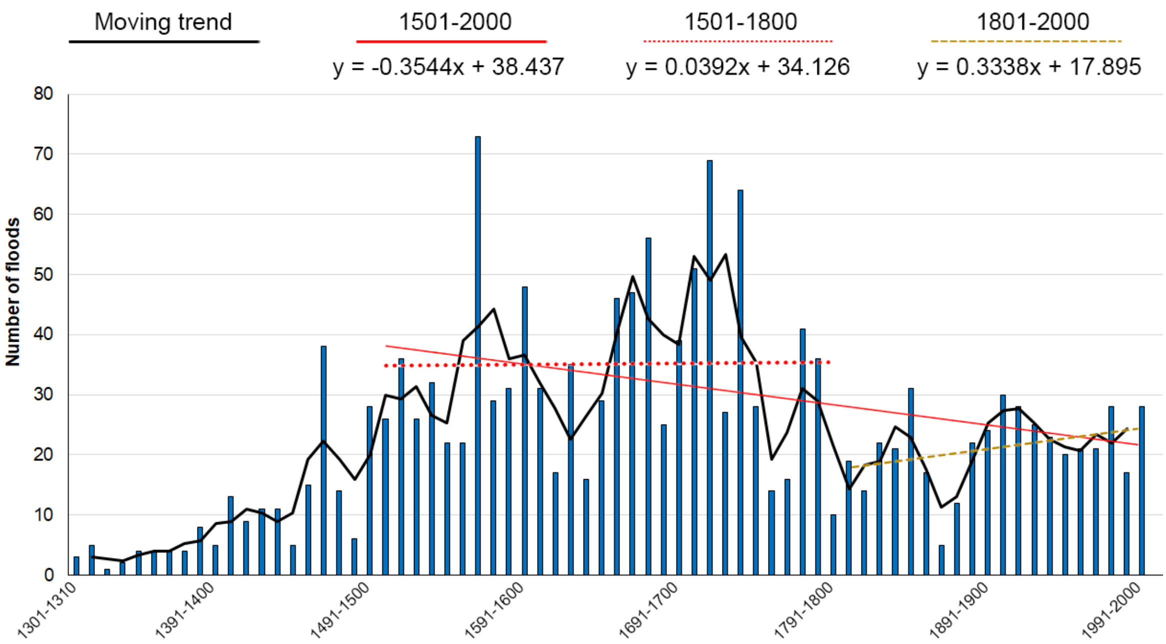

Fig. 13. Trends in flood frequency in Poland in 14th–20th centuries based on 10-year flood totals

It is worth noting that, although no change in flood frequencies was noted in the period 1501–1800, a clear decrease in flood occurrences started around the middle of the 18th century and lasted until the turn of the 20th century (Fig. 13). In the 20th century, a significant increase in number of floods is observed, and this tendency will continue to rise, according to scenarios presented by climatic models (Alfieri et al., 2015; Guerreiro et al., 2018; Tabari, 2020).

The evaluation of century-long trends in Poland in the period 1301–2000 using decadal number of floods is shown in Fig. S8. For the first four centuries, trends are positive, but they are statistically significant (p-value < 0.05) only in the 14th and 17th centuries. Such observed tendencies, however, mean that from the 14th century until the 17th century, floods were always more frequent in the second part of the each analyzed century than in the first. This tendency changed in the 18th century, when a decreasing trend was noted that is also seen (although less clearly) in the 19th and 20th centuries (Fig. S8).

Out of all categories of floods we distinguished, the most extreme ones are of particular interest due to global warming and the expectation that they will greatly increase in frequency and intensity in the future. For this reason, we decided also to investigate their changes (including trends) in Poland in the period 1001–1800. For analysis, we extracted floods classified as “category 3” in Brázdil et al. (2006), and “category 2” in Barriendos and Coeur (2004) classifications (Fig. 14).

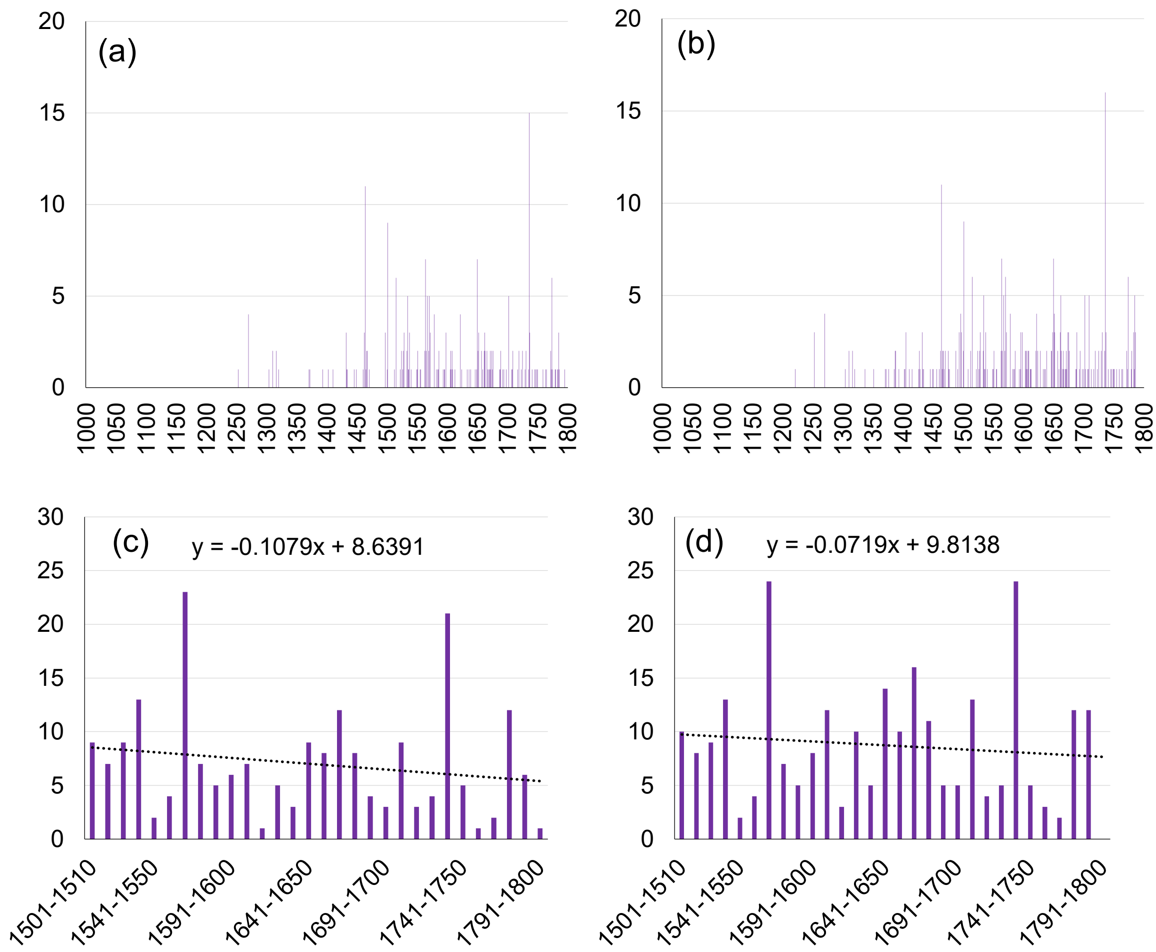

Fig. 14. Number of extreme floods (bars) in Poland in 11th–18th centuries in years (a, b) and decades (c, d), and their trends (dashed lines)

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

Results revealed that, for both classifications, there were decreasing statistical trends (p-value < 0.05) in the number of extreme flood occurrences in the period 1501–1800, while all floods show no trend (compare Fig. 14 and 13). Two 40-year periods can be distinguished that, according to both criteria, have the highest frequency of extreme floods: 1501–40 and 1651–90. Interestingly, the exceptionally high number (between 20 and 25) of decadal extreme floods (1561–70, 1731–40) did not occur in either of these two periods (see Fig. 14).

Discussion

Uncertainties and biases in the documentary evidence are a great challenge in the reconstruction of extreme water phenomena like historical floods (Brázdil et al., 2005b). That is why we tried in our research to eliminate their influence as much as possible, including by taking into account for analysis the most reliable sources. In the paper, we present the most comprehensive and detailed results of our research on the history of floods in Poland in the last millennium, which should significantly enrich knowledge of this phenomenon for Central Europe also. To discuss the results in detail, we first compared our results against other available information about historical floods in Poland that had been presented in some earlier publications; e.g. Majewski (1993), Bielański (1997), Mudelsee et l.. (2003), Grześ (2008), Kasprzak (2010) and Blöschl el.al. (2020). Only two of the mentioned publications (Grześ, 2008 and Blöschl et al., 2020) present lists of floods for all of Poland. Other literature items provide only regional information about floods. For example, Majewski (1993) and Bielański (1997) investigated floods for parts of the Vistula River (Vistula Delta and Upper Vistula, respectively). On the other hand, Mudelsee et al. (2003) and Kasprzak (2010) gathered information about historical floods only for the Oder River.

In this research, assessment of flood occurrences in Poland showed that 1,252 floods (522 in Vistula River basin, and 671 in the Oder River basin) occurred in the 11th–18th centuries. The number of floods provided in our study is significantly greater than numbers given in previous studies (see Table 1, and Table S7). This relation is seen in all distinguished time periods.

Table 1. Comparison of number of floods in Poland in the period 1001–1800 according to various sources

Period	Current study		Majewski (1993)	Bielański (1997)	Mudelsee et al. (2003)	Grześ (2008)	Kasprzak (2010)	Blöschl et al. (2020)
	Vistula River basin	Oder River basin	Vistula Delta	Upper Vistula River	Oder River basin	Vistula and Oder basins	Oder River basin	Vistula and Oder basins
1001–1500	82	96	51	16	19	112	46	N/A
1501–1600	84	245	36	19	39	88	47	67
1601–1700	169	168	29	11	44	31	13	39
1701–1800	187	162	16	3	30	39	26	31

It is also very interesting to investigate whether there exists some coherence between flood occurrences in Poland and in other Central European countries. To address this issue, the results in this study were compared against data on flood occurrences in some Central Europe countries available in literature (Fig. 15). We extracted historical floods for 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; Glaser et al., 2010; Brázdil et al., 2011; Blöschl et al., 2020). It is important in considering this comparison to bear in mind that, due to differences in the availability and reliability of sources, and in the numbers of rivers in the mentioned countries and differences in methods used to distinguished floods, there may be some bias in this comparison.

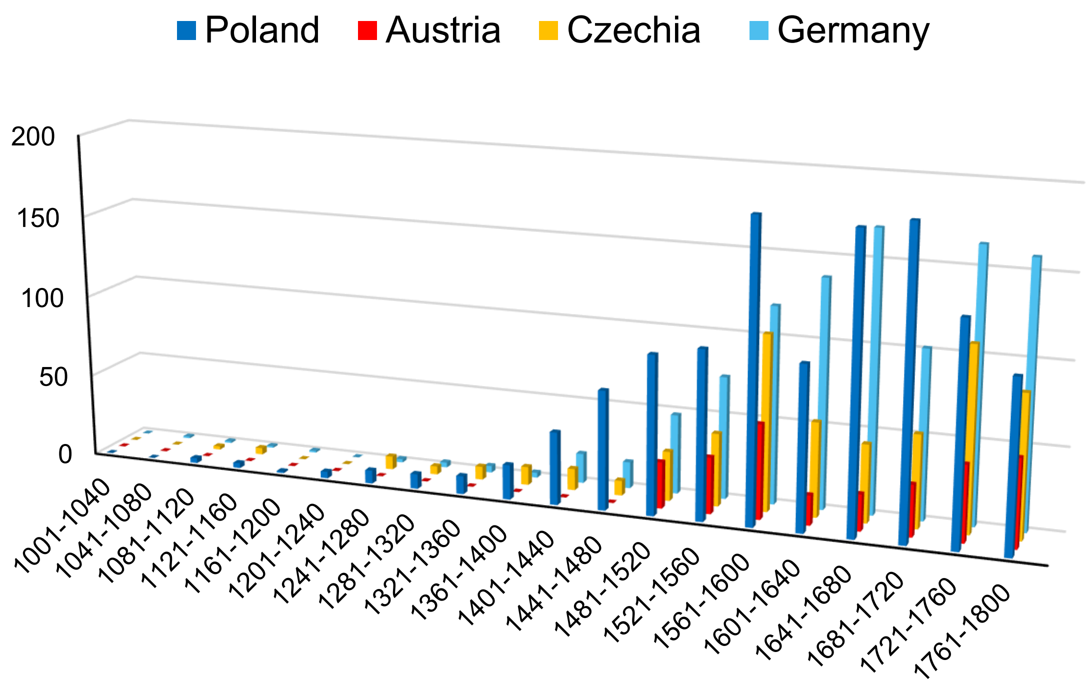

Fig. 15. 40-year number of floods in Poland, Austria, Czechia and Germany in 11th–18th centuries

Based on the comparison of the 40-year frequency of floods in Poland, Austria, Czechia, and Germany illustrated in Fig. 15, the number of floods was greater in Poland and Germany than in Austria and Czechia. Only in the periods 1601–40, 1721–60 and 1761–1800, was the number of floods greater in Germany (138, 164, 159, respectively) than in Poland (99, 133, 103, respectively), while in all other periods, the domination of floods in Poland is seen. It is clear that this is partly related to the variations in the number of sources and rivers for the mentioned countries and to the methodology used in distinguishing floods.

Until the start of the 17th century (in Germany until 1680), there generally exists a good correspondence between all series, which show a steady increase in number of floods, which is strictly connected in all cases with the rising abundance of historical sources. But since the 17th century, this trend has disappeared, and fluctuations in numbers of floods are a common feature in the studied series of floods. Also evident is that the greatest correspondence between the courses of flood numbers is between numbers for Poland and Germany. The most flood-rich periods in these two areas occurred in the periods 1641–80 and 1721–60. In the latter period Czechia saw its largest number of flood, and there was also a relatively high number in Austria (Fig. 15). The most flood-rich period was 1561–1600 for all the countries.

In addition, the statistical significance of trends in flood occurrence in the mentioned countries were carried out based on MK test for the 16th–18th centuries (see Fig. S9). Results demonstrated that, in Poland and Austria, there was no statistically significant trend (p-value > 0.05), while in Czechia and Germany there were increasing statistically significant trends (p-value < 0.05).

Flood frequencies and their trends in Poland, Czechia, and Germany for the last 200–year period are depicted in Fig. S10. The data for this figure for all countries were taken from the dataset provided in Blöschl et al. (2020), while for Poland they were additionally taken from different publications. Analysis of this figure revealed that the number of floods in Poland (428) is clearly smaller than the number of floods in Germany (766) and Czechia (678), but significantly greater than in Austria (49, not shown). The main cause of these differences is the differences in the numbers of rivers for which information on floods is available. For example, the information for the 19th and 20th centuries is available for eight rivers in Germany (Inn, Iller, Isar, Lech, Main, Upper Danube, Salzach, Werra), eight rivers for Czechia (Dyje, Elbe, Morava, Odra, Ohre, Lower Otava, Upper Otava, Vltava) and only two rivers for Austria (Traun, Wien), and Poland (Vistula and Oder). The greatest frequency of floods in this region is seen in the following 30–40-year periods: 1821–50 (Poland), 1821–60 (Czechia), and 1831–70 (Germany). In these periods, the numbers and frequencies of floods are clearly greater in Czechia and Germany than in Poland. Some signs of a flood-rich period in all areas are also seen at the turn of the 20th century, in particular in Poland and Czechia (Fig. S10). The trends for floods in Poland, Czechia, and Germany in 1801–2000 based on their 10-year frequencies are also presented in Fig. S10. Analysis shows that trends in all series of floods are statistically significant based on MK test. However, we need to add that the trend in Poland is upwards, while in Czechia and Germany it is downwards. But in the 20th century, all trends are negative, though they are statistically significant only in Germany and Czechia.

The comparison of moving 30-year trends in flood frequency in Poland (Fig. 13) in this study with trends presented for Central Europe by Glaser et al. (2004) (see their Fig. 2) demonstrated relatively similar trends for the periods 1501–1800 and 1851–2000.

In the assessment of floods intensity, understanding and distinguishing of extreme floods has a great importance due to their devastating consequences. Therefore, in this research, frequencies of extreme floods in Poland in the period 1001–1800 were compared against those available for the neighboring countries of Germany and Czechia (see Table S8) (Brázdil et al., 1999; Mudelsee et al., 2003; Brázdil & Kirchner, 2007; Elleder, 2015; Blöschl et al., 2020). It is important to note that the criteria used by different groups of researchers to distinguish extreme floods are not the same, which may influence the comparison of results. In the studies of historical floods in Poland, only Kowalewski (2006) distinguished extreme floods, but he did not provide the criteria that he used to do so. The mentioned publication lists only 87 extreme floods for Poland in the period of 11^{th}–18^{th} centuries is given. This is significantly lower than the numbers of such floods as identified by us (257 and 347) using the classifications of Brázdil et al. (2006b) (category 3), and Barriendos & Coeur (2004) (category 2) (see Table S8). The number of extreme floods for Czechia and Germany (72 and 119, respectively), was also lower than we found for Poland.

The analysis of spatial variations of flood occurrences in Poland revealed that a great number of floods in the historical period occurred in the Silesia (553, 43%) region, while the number was lowest in Masuria-Podlasie (11, ~1%). The main reasons for this are that historical sources are available in greater numbers for Silesia than for other regions and that the region is bordered by mountains to the south. As a result, there is a high density of rivers, causing this region to be more vulnerable to floods than other regions in Poland. The Silesian region lies almost entirely within the Oder River basin, and therefore, generally, in the 11^{th}–18^{th} centuries, floods were more common in the Oder River basin than in the Vistula River basin.

Documentary evidence in Poland allowed the causes of floods to be described in almost 60% of cases, which is one of the highest such proportions in Europe (see Ghazi et al. 2023a, Ghazi et al. 2023b). On average more than 40% of floods in Poland in the period 1001–1800, even including unknown causes in the statistics, were caused by rain and its subtypes. This finding is in good agreement with the results presented for major rivers in Central Europe by Glaser et al. (2010). The authors of that paper found that long-lasting and convective rains had a great contribution to the occurrences of floods in the period 1500–1800, including in particular the Vistula River and less so the Oder River (where ice break was also another important cause) (see Fig. 3 in their paper).

Out of all seasons, the most floods in Poland in the study period occurred in the summer (46%). These results are aligned with a comprehensive study of flood occurrences in Central European countries (Blöschl et al., 2020). They also found that the season with the most common occurrence of floods was summer (41%), which was only a slightly smaller frequency than for Poland.

There is evidence of increasing extreme events, like floods globally in recent decades due to human-induced climate change (Alifu et al., 2022; Rohde, 2023). Our results showed that, from the end of the Little Ice Age, an increasing trend in flood frequency in Poland is observed (Fig. 13). The sign of the trend changed to negative for the 20th century because in the first 40 years of this century a high frequency of floods was noted (see Fig. S10a). It is worth emphasizing, however, that in the last 30 years the trend has changed again, and we have observed a greater number of floods. This trend is therefore consistent with changes observed in most areas of the globe.

The lack of sufficient instrumental measurements presented a great challenge in identifying and proving possible direct meteorological/climatological causes for flood occurrences before the 19th century. We hope, however, that this work to some degree allows to reduce the existing uncertainty in our knowledge concerning various aspects of flood frequencies (and origins) in Central Europe, but particularly in Poland.

Conclusions

In the current era of climate change, understanding flood frequency, intensity, and origins during history is a significant endeavor. The limited access to instrumental data, especially from before the 19th century, makes it a great challenge for the scientific community to assess flood events before this period. In the presented study, by developing a comprehensive database of historical floods in Poland (https://doi.org/10.18150/VLTVD9) during the 11th–18th centuries according to documentary evidence, we provide comprehensive knowledge about historical hydrology and climatology for Poland. The overarching goal of this research was to contribute to improve the existing studies and completing the knowledge gap in studies of floods before the 21st century (but particularly for before the instrumental period) in Central Europe.

The findings in this research are summarized below:

1. In Poland, there were 1,680 floods in the last millennium and 1,252 in the pre-instrumental (historical) period (1001–1800).
2. In the historical period, floods in Poland were most frequent in the Oder River basin (55% cases), and then in the Vistula River basin (43%).
3. Floods in the period 1001–1800 were most numerous in the regions of Silesia (43%), Baltic Coast and Pomerania (23%), and Lesser Poland (17%).
4. The most common intensities of flood were category. 2 ("above-average, or supra-regional flood") after Brázdil et al. (2006) and category. 1 ("extraordinary") after Barriendos & Coeur (2004), at 33% and 70%, respectively.

5. Summer was the most flood-prone season (46% of all cases), whereas autumn was the least (8%). The most flood-prone month was July (19%), and the least was November (1.9%).
6. The causes of ~60% of floods in Poland in 1001–1800 could be assessed. Rain and its subtypes (classification of flood origins proposed by Lambor [1954]) was the most common cause (44% of all cases with known cause).
7. Flood frequencies in Poland exhibited decreasing and increasing statistically significant trends for 1501–2000 and 1801–2000, respectively. The trend for 1501–1800 was statistically insignificant.
8. During the 11th–18th centuries, floods were more frequent in Poland and Germany than in Czechia and Austria.

CRediT authorship contribution statement

Babak Ghazi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Rajmund Przybylak**: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Funding acquisition, Project administration, Validation, Supervision, Writing – original draft, Writing – review & editing. **Piotr Oliński**: Investigation, Data curation, Validation. **Aleksandra Pospieszyńska**: Data curation, Validation, Software, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The dataset of flood records for Poland during the 11th–18th centuries is available at (https://doi.org/10.18150/VLTVD9). Other data used in this research are available from the corresponding author upon reasonable request.

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