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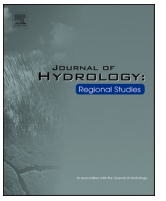

A comprehensive study of floods in Poland in the 17th–18th centuries

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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.

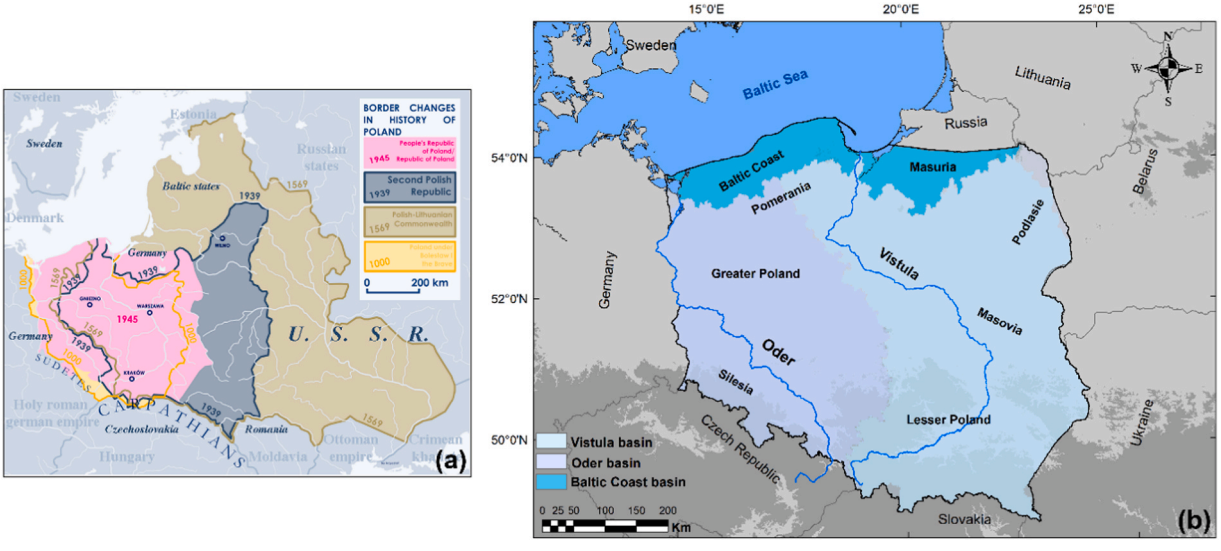

Fig. 1. (a) Changes to the borders of Poland in historical times (source: https://commons.wikimedia.org/wiki/File:Border_changes_in_history_of_Poland.png) (b), Geographical location of contemporary Poland and main river basins.

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

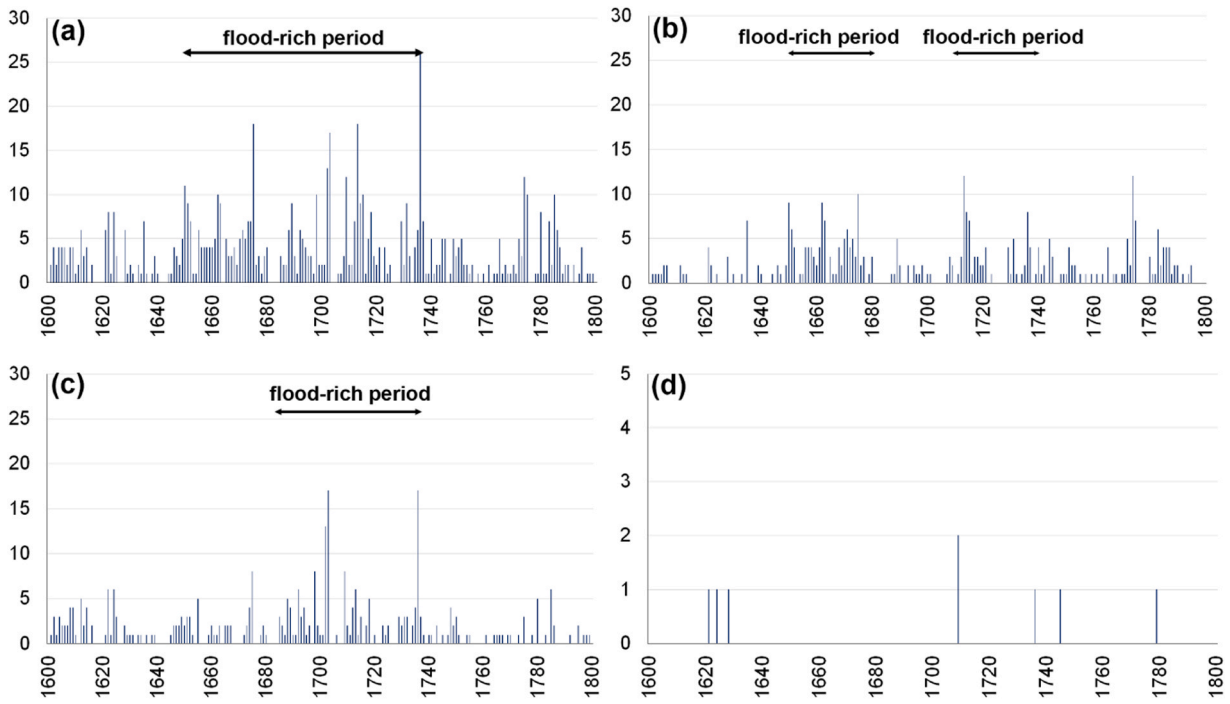

Fig. 2. Number of floods in Poland, AD 1601–1800: (a), All river basins in Poland, (b) Vistula River basin, (c) Oder River basin, (d) Baltic Coast rivers basin.

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

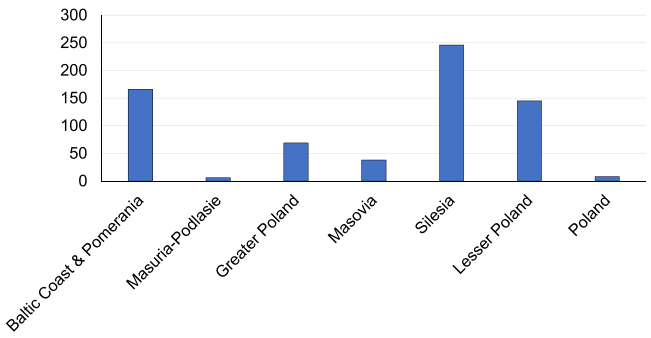

Fig. 3. Number of floods in Poland in the 17th–18th centuries in the six-main regions and miscellaneous category "Poland".

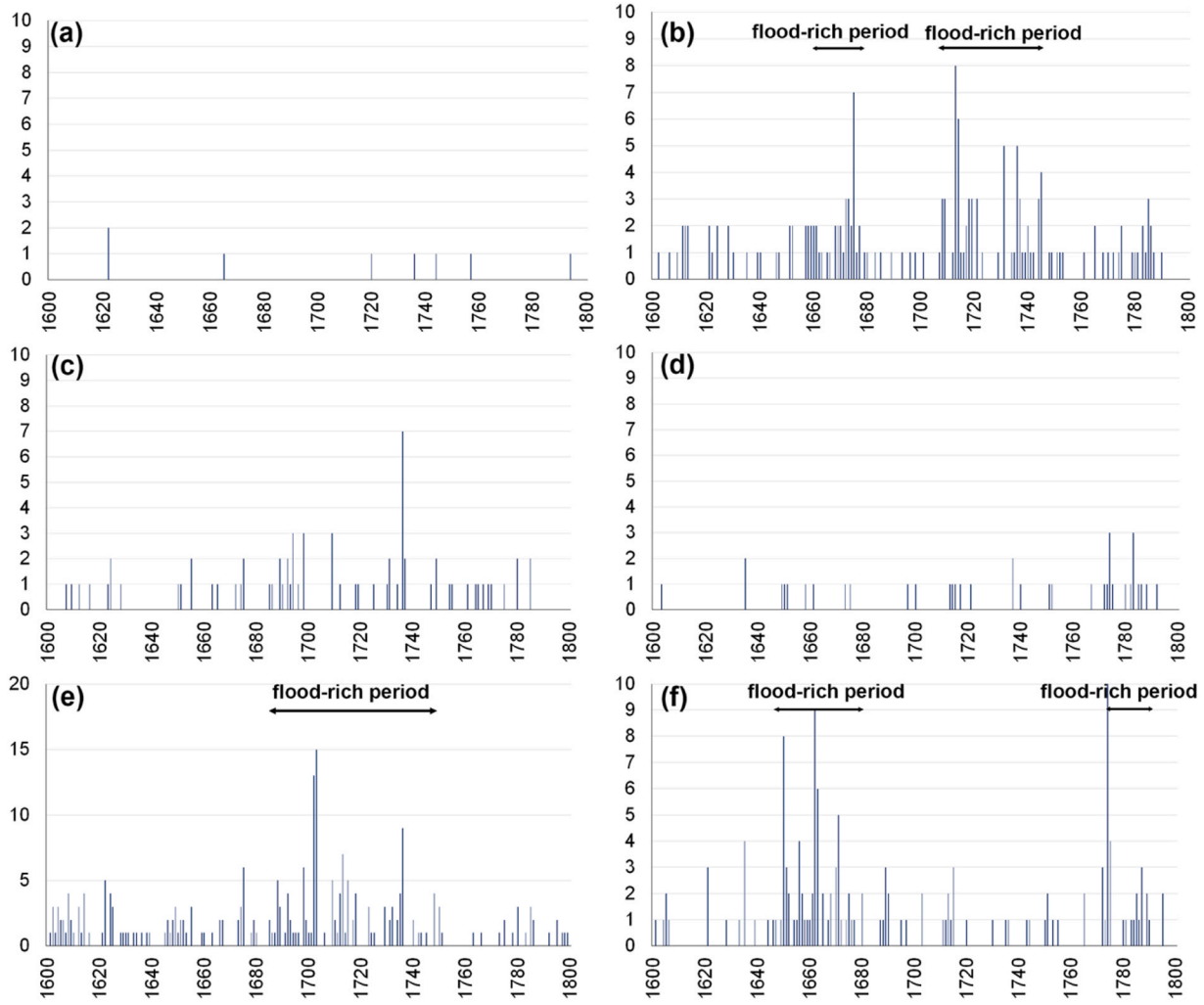

Fig. 4. Number of floods in the 17th–18th centuries, (a) miscellaneous category "Poland" (b) Baltic Coast and Pomerania, (c) Greater Poland, (d) Masovia, (e) Silesia and (f) Lesser Poland. Note: Due to the small number of floods in Masuria-Podlasie region, this region not shown (see Fig. 3).

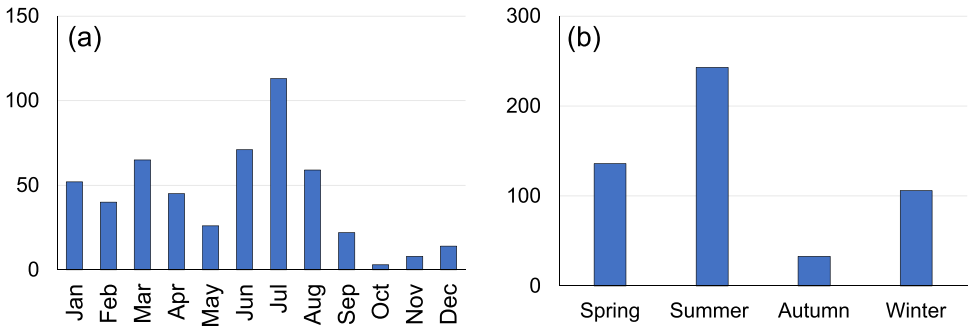

Fig. 5. Frequency of floods (a) by month and (b) by season.

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

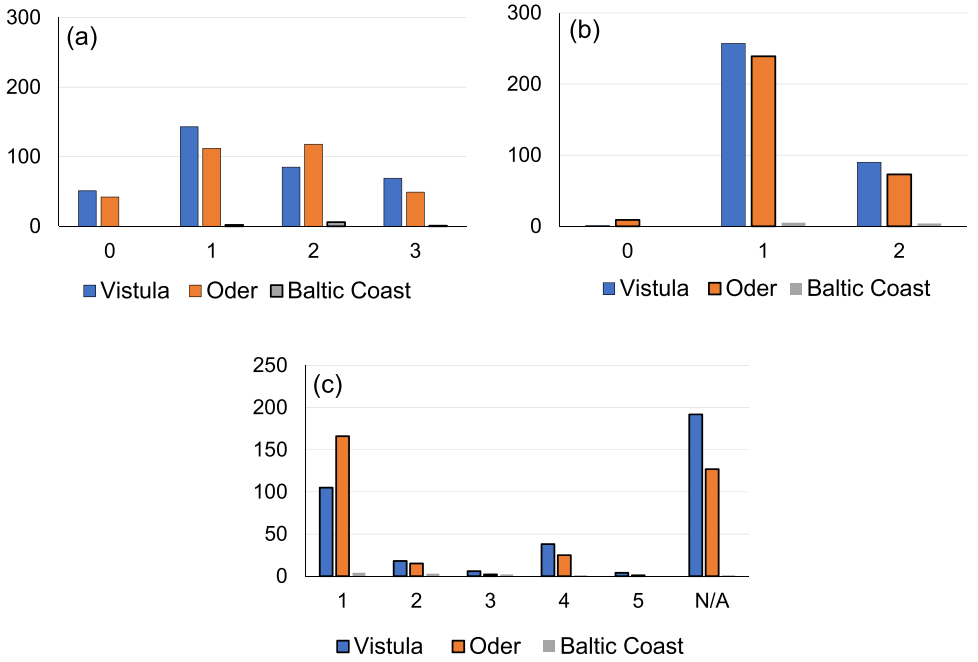

Fig. 6. Number of floods in Poland in period 1601–1800 based on the classifications of: (a) Brázdil et al. (2006b), (b) Barriendos and Coeur (2004), and (c) Lambor (1954), see Table S3 and S4 for classification details. Key: N/A – information not available.

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

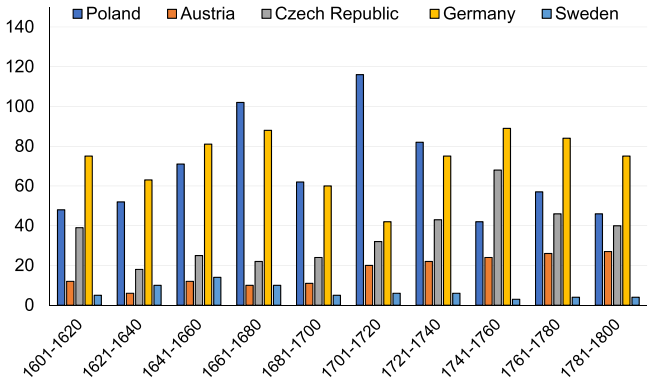

Fig. 7. Frequency of floods in the 17th–18th centuries in Central Europe.

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

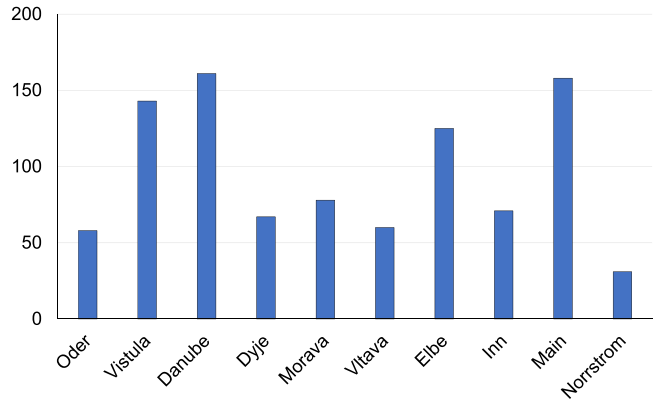

Fig. 8. Number of floods in main Central Europe rivers and in Sweden in the period 1601–1800.

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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