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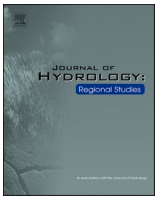

An assessment of flood occurrences in Poland in the 16th century

Babak Ghazi [a,*], Rajmund Przybylak [a,c], Piotr Oliński [b,c], Waldemar Chorążyczewski [b,c], Aleksandra Pospieszyńska [a,c]

[a] Department of Meteorology and Climatology, Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University, Toruń, Poland
[b] Department of Medieval History and Auxiliary Sciences of History, Faculty of Historical Sciences, Nicolaus Copernicus University, Toruń, Poland
[c] Centre for Climate Change Research, Nicolaus Copernicus University, Toruń, Poland

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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.

* Corresponding author.
E-mail address: babak.ghazi@doktorant.umk.pl (B. Ghazi).

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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.

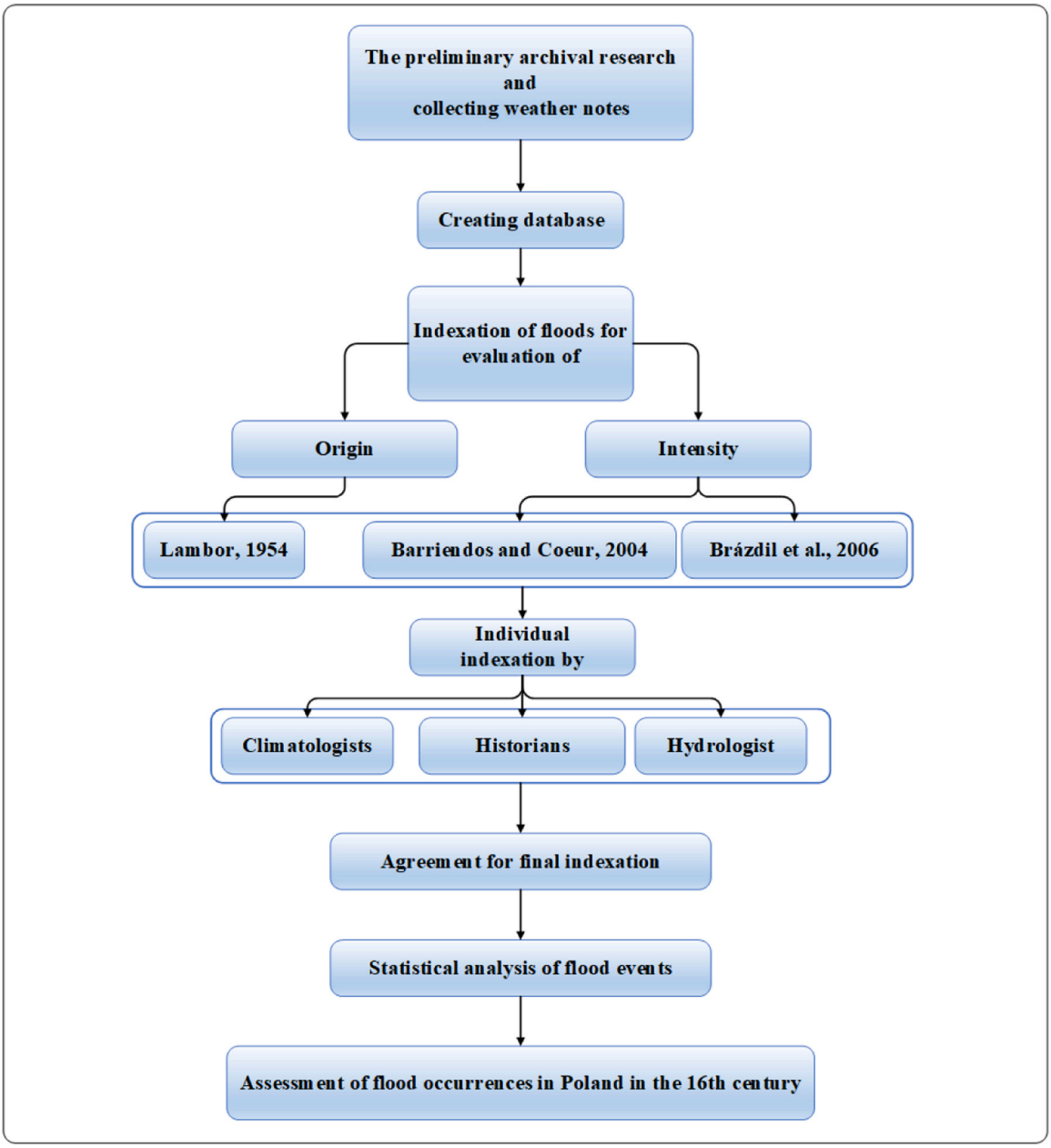

Fig. 2. Research elaboration procedure.

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, 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), 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 (7), 1596 (2), 1598 (6), 1599 (3), 1600	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

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

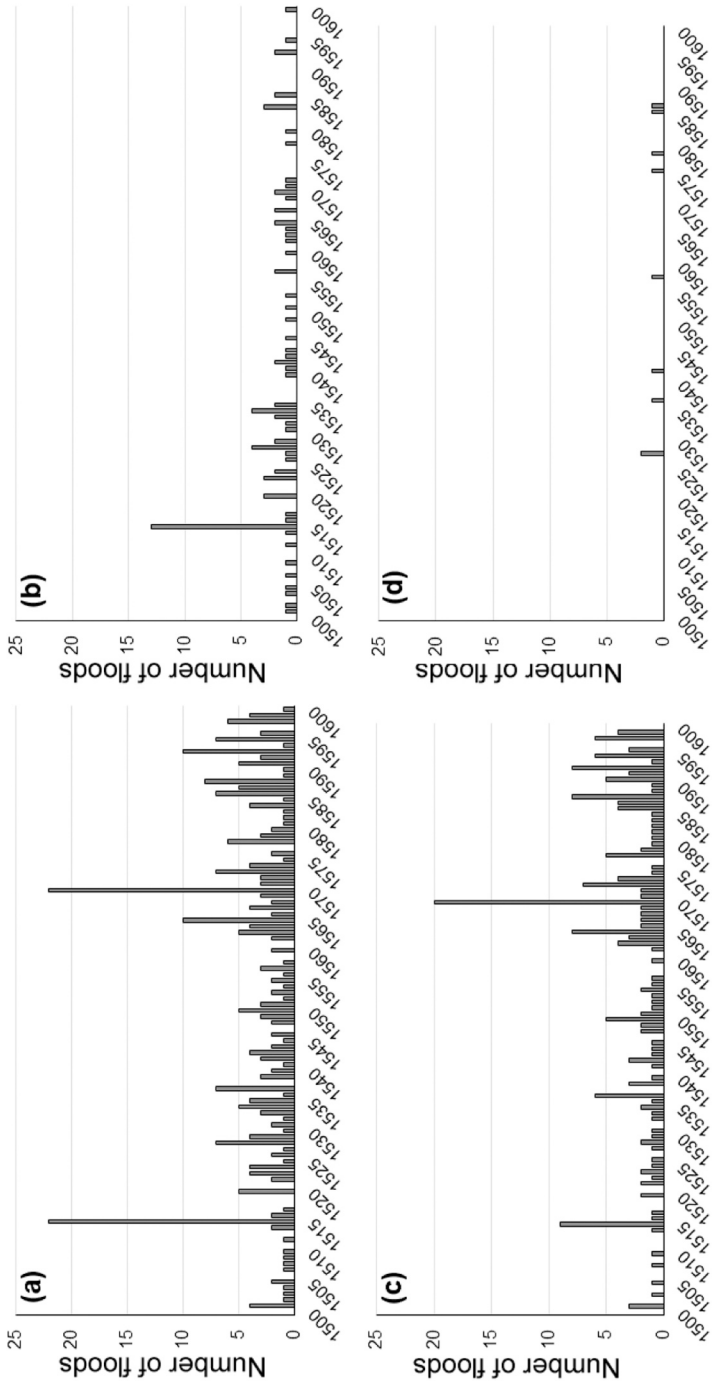

Fig. 3. Number of floods in Poland, AD 1501–1600: (a), all of Poland, (b) Vistula River basin, (c) Oder River basin, (d) Baltic Coast rivers basin.

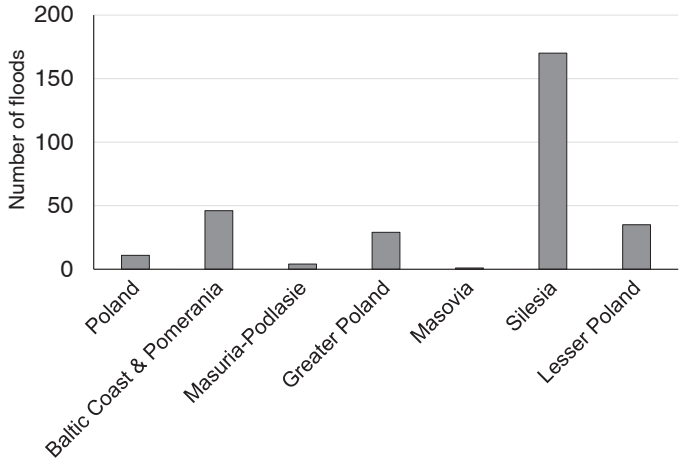

Fig. 4. Number of floods in Poland during the 16th century based on geographical location.

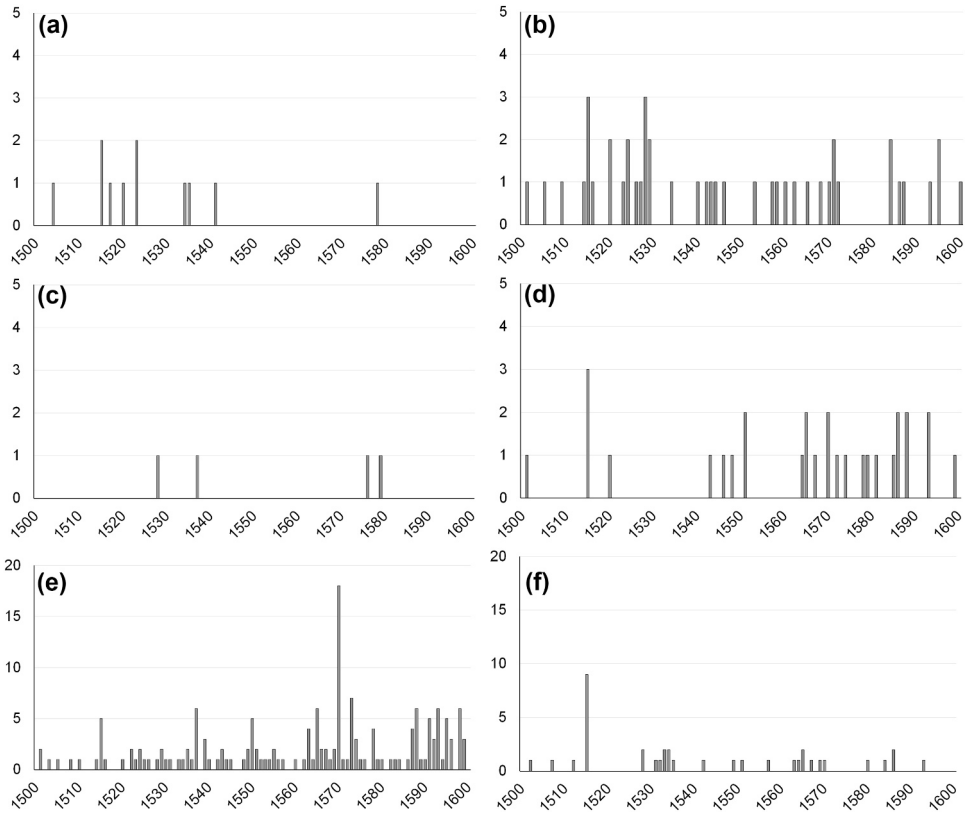

Fig. 5. Number of floods based on regions for the study period, (a) Poland, (b) Baltic Coast and Pomerania, (c) Masuria-Podlasie, (d) Greater Poland, (e) Silesia and (f) Lesser Poland. Note: Floods in Masovia region not shown because only one case was documented (see Fig. 3).

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

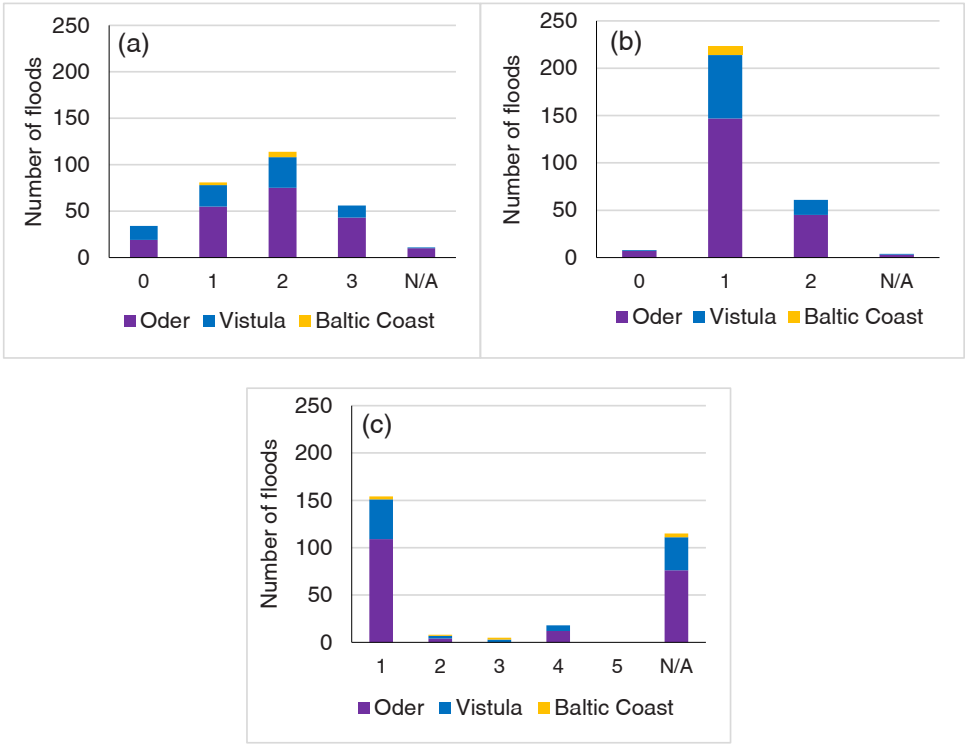

Fig. 6. Number of floods in Poland during the 16th century for river basins based on classifications of: (a) Brázdil et al. (2006b), (b) Barriendos and Coeur (2004), and (c) Lambor (1954). Key: N/A – information not available.

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 (Kowalewski, 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).

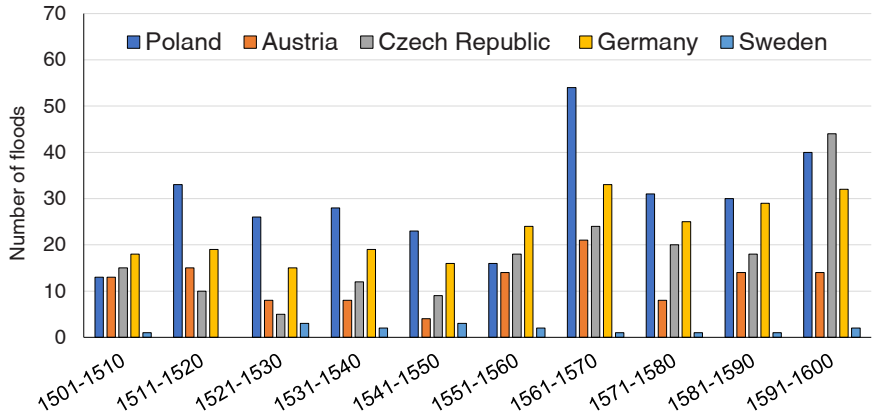

Fig. 7. Comparison of numbers of floods for Poland, Austria, Czech Republic, Germany and Sweden in the 16th century.

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.

References

Alcoforado, M.J., Silva, L.P., Amorim, I., Fragoso, M., Garcia, J.C., 2021. Historical floods of the Douro River in Porto, Portugal (1727–1799). Clim. Change 165 (1), 1–20.

Barriendos, M., & Coeur, D. (2004). Flood data reconstruction in historical times from non-instrumental sources in Spain and France. Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation. Methodological Guidelines, edited by: Benito, G. and Thorndycraft, VR, Centro de Ciencias Medioambientales, Madrid, Spain, 29-42.

Benito, G., Díez-Herrero, A., Fernández de Villalta, M., 2003. Magnitude and frequency of flooding in the Tagus basin (Central Spain) over the last millennium. Clim. Change 58 (1–2), 171–192.

Benito, G., Castillo, O., Ballesteros-Cánovas, J.A., Machado, M., Barriendos, M., 2021. Enhanced flood hazard assessment beyond decadal climate cycles based on centennial historical data (Duero basin, Spain). Hydrol. Earth Syst. Sci. 25 (12), 6107–6132.

Bielański, A.K. (1997). Materiały do historii powodzi w dorzeczu Górnej Wisły: na podstawie rękopisu Adama Kazimierza Bielańskiego i materiałow Jana Fiszera. Politech.

Blöschl, G., Hall, J., Parajka, J., Perdigão, R.A., Merz, B., Arheimer, B., Borga, M., 2017. Changing climate shifts timing of European floods. Science 357 (6351), 588–590.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A., Parajka, J., Merz, B., Bilibashi, A., 2019. Changing climate both increases and decreases European river floods. Nature 573 (7772), 108–111.

Blöschl, G., Kiss, A., Viglione, A., Barriendos, M., Böhm, O., Brázdil, R., Macdonald, N., 2020. Current European flood-rich period exceptional compared with past 500 years. Nature 583 (7817), 560–566.

Brázdil, R., & Kirchner, K. (2007). *Vybrané přírodní extrémy a jejich dopady na Moravě a ve Slezsku (Selected Natural Extremes and Their Impacts in Moravia and Silesia)*. Masarykova univerzita Brno.

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V.,. Tolasz, R. (2005a). Historické a současné povodně v České republice: Masarykova univerzita v Brně, Český hydrometeorologický ústav v Praze.

Brázdil, R., Glaser, R., Pfister, C., Dobrovolný, P., Antoine, J.-M., Barriendos, M., Guidoboni, E., 1999. Flood events of selected European rivers in the sixteenth century. Clim. Change 43 (1), 239–285.

Brázdil, R., Pfister, C., Wanner, H., von Storch, H., Luterbacher, J., 2005b. Historical climatology in Europe – the state of the art. Clim. Change 70, 363–430. https://doi.org/10.1007/s10584-005-5924-1.

Brázdil, R., Dobrovolný, P., Elleder, L., Kakos, V., Kotyza, O., Květoň, V., Máckova, J., Müller, M., Štekl, J., Tolasz, R., H, a V., 2006a. Historical and recent floods in the Czech Republic: causes, seasonality, trends, impacts. In *Flood risk management: hazards*. vulnerability and mitigation measures. Springer,, pp. 247–259.

Brázdil, R., Kundzewicz, Z.W., Benito, G., 2006b. Historical hydrology for studying flood risk in Europe. Hydrol. Sci. J. 51 (5), 739–764.

Brázdil, R., Řezníčková, L., Valášek, H., Havlíček, M., Dobrovolný, P., Soukalová, E., Skokanova, H., 2011. Fluctuations of floods of the River Morava (Czech Republic) in the 1691–2009 period: interactions of natural and anthropogenic factors. Hydrol. Sci. J. Des. Sci. Hydrol. 56 (3), 468–485.

Cœur, D., Lang, M., 2008. Use of documentary sources on past flood events for flood risk management and land planning. Comptes Rendus Geosci. 340 (9–10), 644–650.

Cyberski, J., Grześ, M., Gutry-Korycka, M., Nachlik, E., Kundzewicz, Z.W., 2006. History of floods on the River Vistula. Hydrol. Sci. J. 51 (5), 799–817.

Desai, B., Maskrey, A., Peduzzi, P., De Bono, A., & Herold, C. Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction http://archive-ouverte.unige.ch/unige:78299 (UNISDR, 2015).

Ghazi, B., Przybylak, R., Oliński, P., Bogdańska, K., Pospieszyńska, A., 2023. The frequency, intensity, and origin of floods in Poland in the 11th–15th centuries based on documentary evidence. J. Hydrol., 129778

Glaser, R., Stangl, H., 2003. Historical floods in the Dutch Rhine delta. Nat. Hazards Earth Syst. Sci. 3 (6), 605–613.

Glaser, R., Stangl, H., 2004. Climate and floods in Central Europe since AD 1000: data, methods, results and consequences. Surv. Geophys. 25 (5–6), 485–510.

Glaser, R., Riemann, D., Schönbein, J., Barriendos, M., Brázdil, R., Bertolin, C., van Engelen, A., 2010. The variability of European floods since AD 1500. Clim. Change 101 (1), 235–256.

Grześ, M. (2008). Historia powodzi na Wiśle w świetle tablic wielkich wód, unpublished conference paper, http://www.wielkawoda.umk.pl/czym_sa_znaki/index.html.

IPCC. (2021). Climate change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Kasprzak, M. (2010). Wezbrania i powodzie na rzekach Dolnego Slaska. Wyjatkowe zdarzenia przyrodnicze na Dolnym Slasku i ich skutki, edited by: Migon, P., Rozprawy Naukowe Instytutu Geografii i Rozwoju Regionalnego Uniwersytetu Wrocławskiego, 14, 81-140.

Kiss, A., Laszlovszky, J., 2013. 14th-16th-century Danube floods and long-term water-level changes in archaeological and sedimentary evidence in the western and central Carpathian Basin: An overview with documentary comparison. J. Environ. Geogr. 6 (3–4), 1–11.

Lambor, J., 1954. Klasyfikacja typów powodzi i ich przewidywanie. Gospod. Wodna 14 (4), 129–131.
Majewski, A., 1993. Kronika Powodzi w delcie Wisły. In: Churski., Z. (Ed.), Uwarunkowania przyrodnicze i społeczno-ekonomiczne zagospodarowania dolnej Wisły. Instytut Geografii, Uniwersytet Mikołaja Kopernika, Toruń, pp. 13–28.
Marchi, L., Borga, M., Preciso, E., Gaume, E., 2010. Characterisation of selected extreme flash floods in Europe and implications for flood risk management. J. Hydrol. 394 (1–2), 118–133.
Mudelsee, M., Börngen, M., Tetzlaff, G., Grünewald, U., 2003. No upward trends in the occurrence of extreme floods in central Europe. Nature 425 (6954), 166–169.
Mudelsee, M., Börngen, M., Tetzlaff, G., Grünewald, U., 2004. Extreme floods in central Europe over the past 500 years: Role of cyclone pathway "Zugstrasse Vb". J. Geophys. Res.: Atmospheres 109 (D23).
Mudelsee, M., Deutsch, M., Börngen, M., Tetzlaff, G., 2006. Trends in flood risk of the River Werra (Germany) over the past 500 years/Tendances du risque d'inondation dans la vallée de la rivière Werra (Allemagne) durant les 500 dernières années. Hydrol. Sci. J. 51 (5), 818–833.
Przybylak, R., Majorowicz, J., Wójcik, G., Zielski, A., Chorążyczewski, W., Marciniak, K., Syta, K., 2005. Temperature changes in Poland from the 16th to the 20th centuries. Int. J. Climatol.: A J. R. Meteorol. Soc. 25 (6), 773–791.
Przybylak, R., Oliński, P., Koprowski, M., Filipiak, J., Pospieszyńska, A., Chorążyczewski, W., Dąbrowski, H.P., 2020. Droughts in the area of Poland in recent centuries in the light of multi-proxy data. Climate 16 (2), 627–661.
Przybylak, R., Oliński, P., Koprowski, M., Szychowska-Krąpiec, E., Krąpiec, M., Pospieszyńska, A., Puchałka, R., 2023. The climate in Poland (central Europe) in the first half of the last millennium, revisited. Climate 19, 2389–2408. https://doi.org/10.5194/cp-19-2389-2023.
Retsö, D., 2015. Documentary evidence of historical floods and extreme rainfall events in Sweden 1400–1800. Hydrol. Earth Syst. Sci. 19 (3), 1307–1323.
Rohr, C., 2006. Measuring the frequency and intensity of floods of the Traun River (Upper Austria), 1441–1574. Hydrol. Sci. J. 51 (5), 834–847.
Rohr, C. (2007). Extreme Naturereignisse im Ostalpenraum: Naturerfahrung im Spätmittelalter und am Beginn der Neuzeit, (Umwelthistorische Forschungen 4).
Stamataki, I., Kjeldsen, T.R., 2021. Reconstructing the peak flow of historical flood events using a hydraulic model: The city of Bath. U. Kingd. *J. Flood Risk Manag.* 14 (3), e12719.
Tarasova, L., Merz, R., Kiss, A., Basso, S., Blöschl, G., Merz, B., Schumann, A., 2019. Causative classification of river flood events. Wiley Interdiscip. Rev.: Water 6 (4), e1353.
Winsemius, H.C., Aerts, J.C., Van Beek, L.P., Bierkens, M.F., Bouwman, A., Jongman, B., Van Vuuren, D.P., 2016. Global drivers of future river flood risk. Nat. Clim. Change 6 (4), 381–385.