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# Flood occurrences and characteristics in Poland (Central Europe) in the last millennium

Babak Ghazi [a,*], Rajmund Przybylak [a,c], Piotr Oliński [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

In the current era of global climate change, extreme events such as flood exposure are increasing globally. Knowledge about floods during historical periods is limited worldwide, mainly due to gaps in the documentary evidence and the lack of a reliable, comprehensive database. A new comprehensive database of floods in Poland in the 11th–18th centuries was created using quality-controlled documentary evidence. In addition, a list of floods for the 19th and 20th centuries was created based on a literature review. Using all these data, the frequency, intensity, genesis, and spatial distribution of floods in Poland in the last millennium were investigated. Results revealed the occurrence of 1680 floods in Poland in the last millennium. The 18th century was the most abundant in recorded floods (356, 21 %). Floods in the 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 %). An investigation of the origin of floods indicated that rain was the main contributing factor to the 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 %). Analysis of the multi-temporal trend demonstrated that, overall, for the periods of 1501–1700 and 1601–1800, positive trends were more numerous than negative trends, whereas, for 1801–2000, negative trends were slightly more numerous than positive trends.

## 1. Introduction

Floods are one of the most common weather-related natural hazards, causing devastating impacts worldwide, including fatalities (Liu et al., 2022). For example, according to the latest estimates, in the past 30 years, they caused half a million deaths (Doocy et al., 2013; CRED, 2015; Lee et al., 2018; Gu et al., 2020). 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). However, according to the findings presented by Lee et al. (2018), this tendency is still not observed globally. They even found that "global floods tended to decrease in magnitude, frequency, and duration during 1960–2014". On the other hand, on a regional scale, such as in Europe, both increasing and decreasing trends were noted in the period 1960–2010 (Blöschl et al., 2019). The latter, however dominated, in particular in southern and eastern Europe, including Poland. Also, Schulte et al. (2019), found that the 20th century was not an exceptional flood period. On the other hand, they estimated that the Little Ice Age was a particularly flood-rich period. This indicates that we still have limited knowledge about global flood changes. More research is needed to improve the interpretation of the flood series. According to Schulte et al. (2019), the interpretation is very complex because "landscapes and flood drivers are heterogeneous and systems show different sensitivities to flood control and drivers".

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 on the Oder River (Mudelsee et al., 2004); (ii) in 2010 in Poland, Austria, Czechia, Hungary, Slovakia, and Serbia (Bryndal, 2015); (iii) in 2013 on 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 annual economic losses due to flood-related phenomena (Feyen et al., 2020). In the case of Poland, three catastrophic floods that recently occurred in 1997, 2001 and 2010 caused

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

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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 and Bogdańska-Warmuz, 2012; Kundzewicz et al., 2023). According to Lorenc (2012), of all meteorological, climate and water events, floods are the most catastrophic, being responsible for the greatest material losses. The major flood that occurred in September 2024 in Silesia again showed how devastating floods are in Poland. Thus, due to the adverse societal and environmental consequences inherent to floods, the assessment of flood events remains an important task for the scientific community. In particular, it is important to have a better knowledge of spatial-temporal flood occurrences and their origins from a long-term perspective. Such knowledge can provide a clear insight into this complex phenomenon, but it is still not well understood, even for the latest decades (Liu et al., 2022).

In Poland, according to Czaja (2011), the oldest preserved systematic records of water gauge measurements are available only for short periods: 1717 (Wrocław), 1739 (Gdańsk) and 1760–1772 (Toruń). Unfortunately, for many areas (including Poland) knowledge about long-term changes in flood occurrences, especially before the instrumental period, is very limited. That is why, for the area of Poland, a great effort was undertaken by an interdisciplinary team of authors, including climatologists, historians and hydrologists, to create a new comprehensive database of floods occurring in the period 1001–1800 (for details, see the Data and methods sub-section). For this purpose, the best sources of information are written notes about past weather (documentary evidence), which very often contain precise information about the time of a flood occurrence, spatial coverage, damage, etc. Other possible proxy data (tree scars, tree-ring data, sediments, etc.) are usually limited to information about the year of flood occurrence. Moreover, reconstructed floods in Poland using injuries in trees cover only the last 200 years, which is limited by the age of living conifer trees. Good examples of such reconstruction are available for the Lower Vistula based on tree scars (Pawłowski, 2003), and for the Tatra Mountains using dendrogeomorphic analysis of injuries to trees (Ballesteros-Cánovas et al., 2015; Ballesteros-Cánovas et al., 2016a; Ballesteros-Cánovas et al., 2016b). On the other hand, for the study period (1001–1800), some information about floods, albeit very limited and general (except for individual major floods), can also be obtained from, among others, geologic-geomorphological (sediments) and archaeological records (Starkel, 2001; Schulte et al., 2019; Díez-Herrero et al., 2024). As was mentioned earlier, many aspects of flood occurrences in the area of Poland in the study period 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 period 1001–1800 using all available information gathered in the mentioned database.

For the present research, for some comparison purposes (mainly frequency of flood occurrence), we further created a list of flood occurrences for the 19th–20th centuries using information available in the literature (Majewski, 1993; Bielański, 1997; Mudelsee et al., 2003; Grześ, 2008; Kasprzak, 2010; Blöschl et al., 2020). The details that we present in the paper are usually not available in the mentioned papers.

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 previous studies (Ghazi et al., 2023a; Ghazi et al., 2023b; Ghazi et al., 2024). The outputs of this study present a comprehensive picture of historical hydrology and climatology studies in Central Europe and complete the knowledge gap for historical flood studies in Poland.

## 2. Study area

Poland is located in Central Europe between the Baltic Sea in the north and the Sudetes and Carpathians in the south (Fig. 1). 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, Masuria-Podlasie, Greater Poland, Masovia, Silesia and Lesser Poland (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".

## 3. Data and methods

To conduct this research, we used the latest version of the database of historical floods in Poland in the 11th–18th centuries (https://doi.org/10.18150/VLTVD9). The database is based mainly on three earlier prepared databases for three sub-periods (11th–15th, 16th, and 17th–18th centuries (Ghazi et al., 2023a; Ghazi et al., 2023b; Ghazi et al., 2024) but has been updated by the addition of some new floods discovered recently in documentary evidence (see Table S1). In addition, we utilized the uniform methodology for distinguishing floods and estimating their characteristics, which was slightly different for each previous database. The database contains 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. This database was created based on various documentary sources such as handwritten and unpublished sources, published sources, and "secondary literature" (See Table S2). 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 were categorized as; 1 – weak, if the information was derived from secondary literature rather than the original source; 2 – moderate, if the information was written centuries after the flood occurrence, and 3 – high, if the information was written in a source in the same period that the flood event occurred and provides precise information. The total number of sources 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.

In Poland, as in most countries, floods 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 of flood information 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

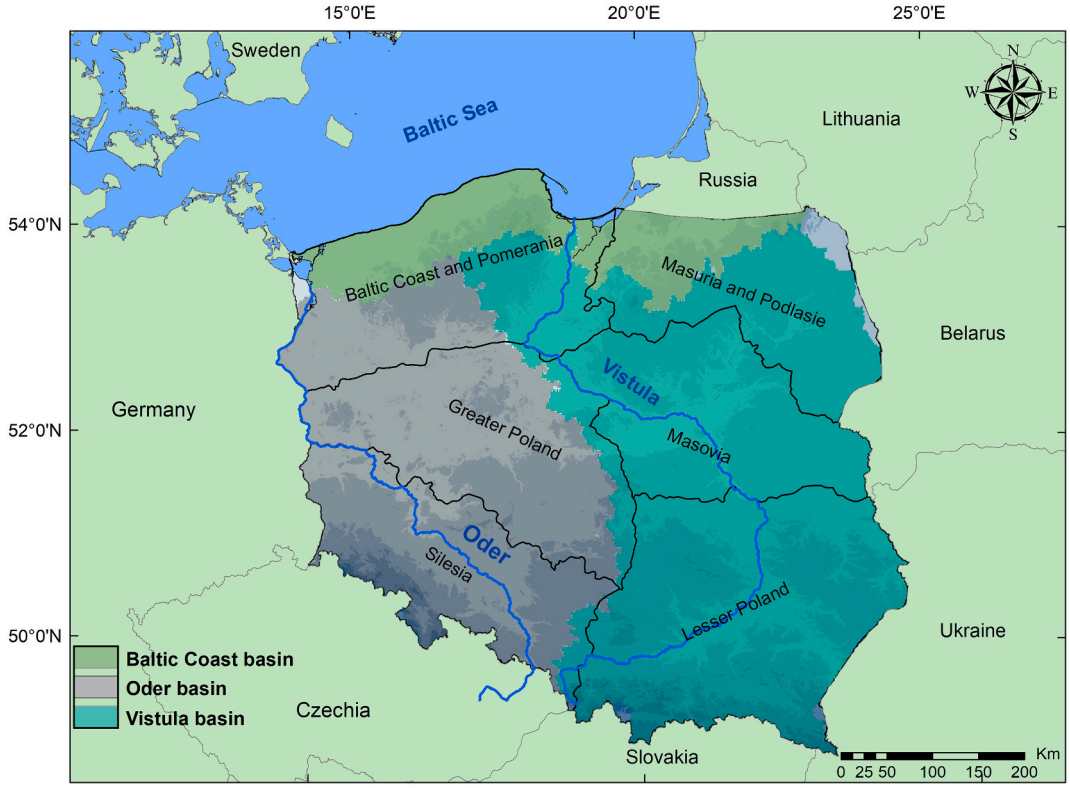


**Fig. 1.** Geographical location of Poland, main regions and river basins.

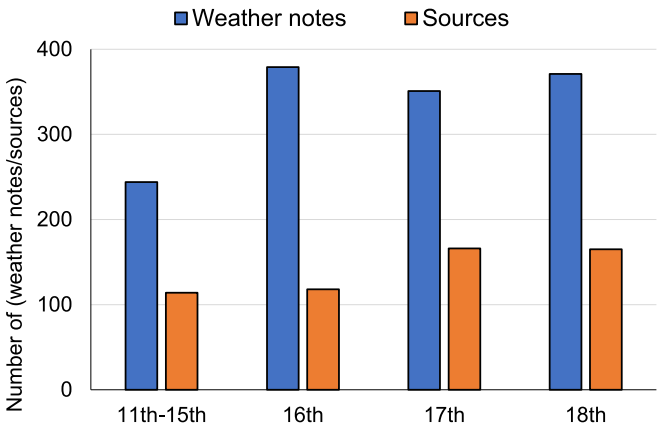


**Fig. 2.** Number of weather notes and sources used to identify floods in Poland in the period 1001–1800.

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 (from the 18th to 20th centuries), especially in monographs on 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 1345 weather notes (see Table S3 and Fig. 2). Similarly, as for historical sources, their numbers are low for the period before 1500 and are later stable, ranging from 351 (17th century) to 379 (16th century). In addition, in the database, the flood intensities were classified based on two methods 1: Brázdil et al. (2006) and 2: Barriendos and Coeur (2004), and the origins of floods were classified according to the method of Lambor (1954) (See Tables S4–S5). In the classification of floods by Brázdil et al. (2006) (Method-1), floods are divided into four categories by intensity: (1) flood, (2) smaller, regional flood, (3) above-average or supra-regional flood, and (4) above-average or supra-regional flood on a disastrous scale. Barriendos and Coeur (2004) (Method-2) distinguished the intensity of floods by defining them as "ordinary", "extraordinary" and "catastrophic". In the indexation of floods by their origin according to the Lambor (1954) method, the cause of floods is described as "1- rain, and its subtypes, 2- snowmelt, 3- storm, 4- winter related floods, and 5- anthropogenic".

The detailed information regarding the procedure for creating the database is available in previous studies (Ghazi et al., 2023a; Ghazi et al., 2023b). In the database of floods, for the category of "Poland", no information about river basins is provided when there is no detailed information about place, regions or river name(s). In addition, if the weather notes contain no clear information about flood occurrences being on two rivers, we assumed them to be two separate independent floods, whereas when there is information that a flood occurred on two rivers that 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 we entered only the river name in the "place" column in the database. 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 a flood if it met the Barriendos and 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 cited earlier. It is worth adding, however, that the information for this period is very limited in comparison to our database for the period 1001–1800. In assessing flood occurrences, for comparison purposes, we use subperiods (i.e., the 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. There are different ways to analyze the trends for hydrological time series. Multi-temporal trend analysis is one of the most robust ways to evaluate trends in time series. This method was originally introduced by Stahl et al. (2010) and modified for hydrological time series by Hannaford et al. (2013). The test evaluated the trend in time series based on the MK Z statistic (MKZ). MKZ follows a standard normal distribution, having a mean of zero and a variance of one. An MKZ value greater than zero suggests an increasing trend, while a value below zero indicates a decreasing trend. To assess statistical significance, a Type 1 error probability of 5 % was used. A two-tailed MK test was applied, meaning that the null hypothesis of "no trend" is rejected if the MKZ value falls outside the ±1.96 range according to conventional statistical testing. This method has been successfully applied in flood studies (Hannaford et al., 2021; Tsiokanos et al., 2023). The MK test is assessed using the following equation:

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

Under the null hypothesis that there is no trend within the time series:

$$E(S) = 0,$$

$$Var(S) = n\,(n-1)\,(2n+5)/18.$$

The test statistic is the standardized value calculated as

$$Z = \begin{cases} \dfrac{s-1}{\sqrt{Var(s)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{s+1}{\sqrt{Var(s)}} & \text{if} \quad S < 0 \end{cases}$$

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 being below the significance level (alpha) ($p < \alpha$), indicates that there is a significant trend in the data series. If the p-value is equal to or greater than alpha ($p \geq \alpha$), it means that there are no significant trends for the dataset.

## 4. Results

The analysis of the documentary evidence yielded records relating to 1252 floods in Poland in the 11th–18th centuries (Table 1 and Fig. 3a). They were less frequently recorded in medieval times (210), mainly due to the evidently smaller number of available historical sources (see Fig. 2). In particular, a small number of floods was noted for before the 14th century (20). Better availability of historical sources for Poland is seen for the 15th century, particularly 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 in this period in comparison to our methodology.

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

| Time period | Year of flood occurrences in Poland in the 11th–18th 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 one in the mentioned year.

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 the Vistula River basin (522 floods). The number of floods in the basins of the Baltic Coast rivers (31 floods) was significantly lower than those for the Oder and Vistula basins.

Assessment of the history of floods in river basins according to different centuries demonstrated that the per-century number of floods in Poland was highest in the 18th century (354) (see Fig. 4 and Fig. S2). In the 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, respectively.

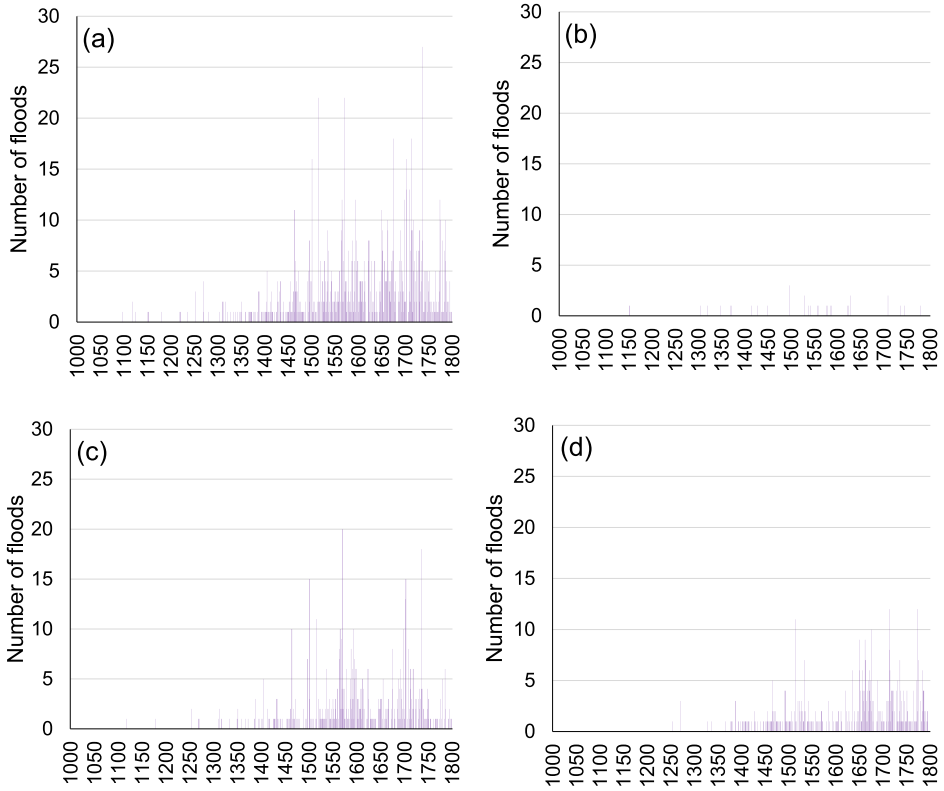


**Fig. 3.** Number of floods in main river basins in Poland, 1001–1800 CE: (a) all river basins in Poland, (b) Baltic Coast rivers basin (c) Oder River basin and (d) Vistula River basin.

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 the 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).

The analysis of the monthly number of floods in Poland in the period 1001–1800 (see Fig. 7a and Fig. S4a) showed that they were recorded most commonly in July (159), August (117) and June (109) and most rarely in December (23), October (16) and November (12). The investigation of the seasonal frequency of floods demonstrated that 46 % of floods occurred in summer (June, July, August) and 27 % in the spring (March, April, May) (Fig. 7b and Fig. S4b). The lowest frequencies of floods were noted in the autumn (September, October, November) and winter (December, January, February) (8 % and 18 %, respectively). This seasonal pattern in flood occurrences in Poland is also observed in each sub-period (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 (JJA) was the main season for flood occurrences.

Results describing flood intensities and origins according to the criteria proposed in the paper are shown in Table S6 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 Method-1 classification and three grades/categories (0–2) using the Method-2 classification (for more details see Table S4). According to the first classification, the most numerous were floods classified as category 2 ("above-average, or supra-regional flood", 408 cases) and category 1 ("smaller, regional flood", 403) (Fig. 8). According to the second classification, category 1 ("extraordinary") was most frequent. The second most frequent group of floods was category 2 ("catastrophic"), but their frequency was about half that of category 1. The third category of floods, distinguished by Method-2, which they called "ordinary" (category 0), was not classified by us as a 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 the Oder River basin (see Table S7).

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 few (77, 62, 23 and 7) were caused by winter-related phenomena (ice jam), snowmelt, storm, and anthropogenic reasons, respectively. The assessment of flood origins by region (Fig. 9) also shows the dominance of rain in this process.

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

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. Analysis of the category 2 floods in Method-2 classification revealed that their relative frequency in Poland was

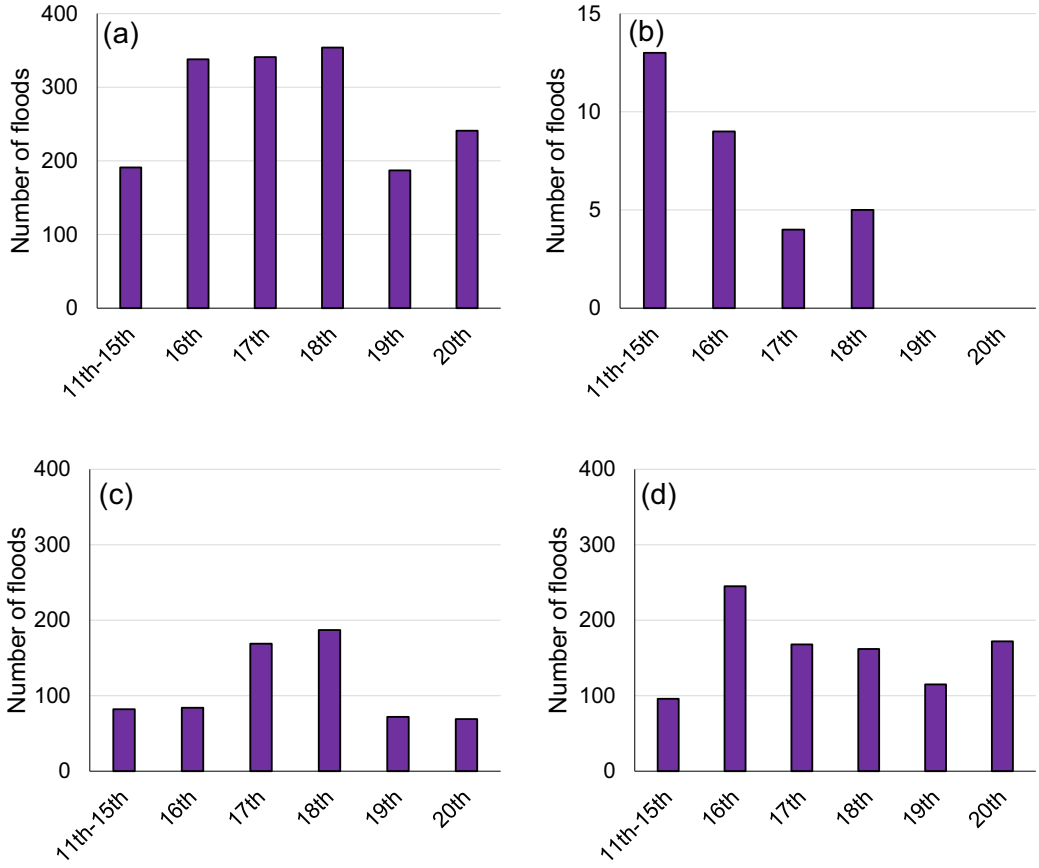


**Fig. 4.** Number of floods in main river basins in Poland in different centuries, 1001–2000: (a) all river basins, (b) Baltic Coast rivers* basin (c) Vistula River basin and (d) Oder River basin.
* Key: there is no record of floods in the 19th and 20th centuries for this area; please note the scale difference in Fig. (b).

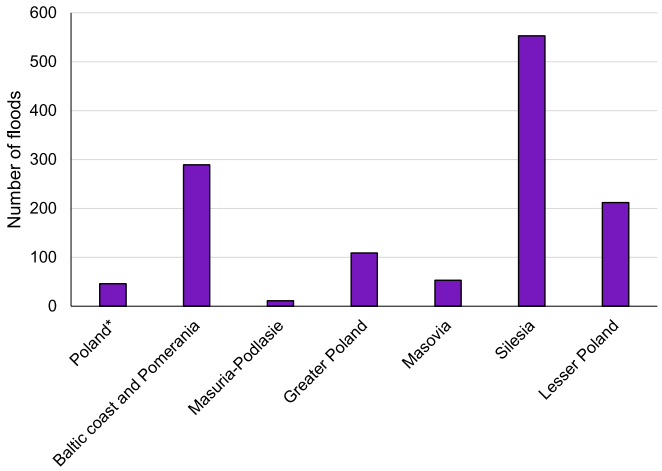


**Fig. 5.** Number of floods in main regions of Poland, 1001–1800 CE.
*Key: category "Poland" with no detail for geographical location of floods.

highest (41 %) in the 11th–15th centuries and only a little over half that in the 18th century (22 %). The same trend in the ratio of extreme floods to all floods, though weaker, is also noted in category "3" of floods according to the Method-1 classification.

The assessment of the origin of floods based on the Lambor (1954) classification by century is depicted in Fig. 11. The results indicated that, for category 1 ("rain and its 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 of 35–45 % for the analyzed sub-periods (Fig. 11b).

Since rain was the main cause of floods in the study area, we also evaluated changes in seasonal flood occurrences for its different categories (including subtypes) (see Fig. S7). It is clear that, for most floods, the historical sources indicated rain as the main cause, but it was not possible to clearly indicate their 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 detailed 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 11th–18th 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 Poland, south-eastern Poland, and central northern Poland (of which, especially the area of the Lower Vistula river). A 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

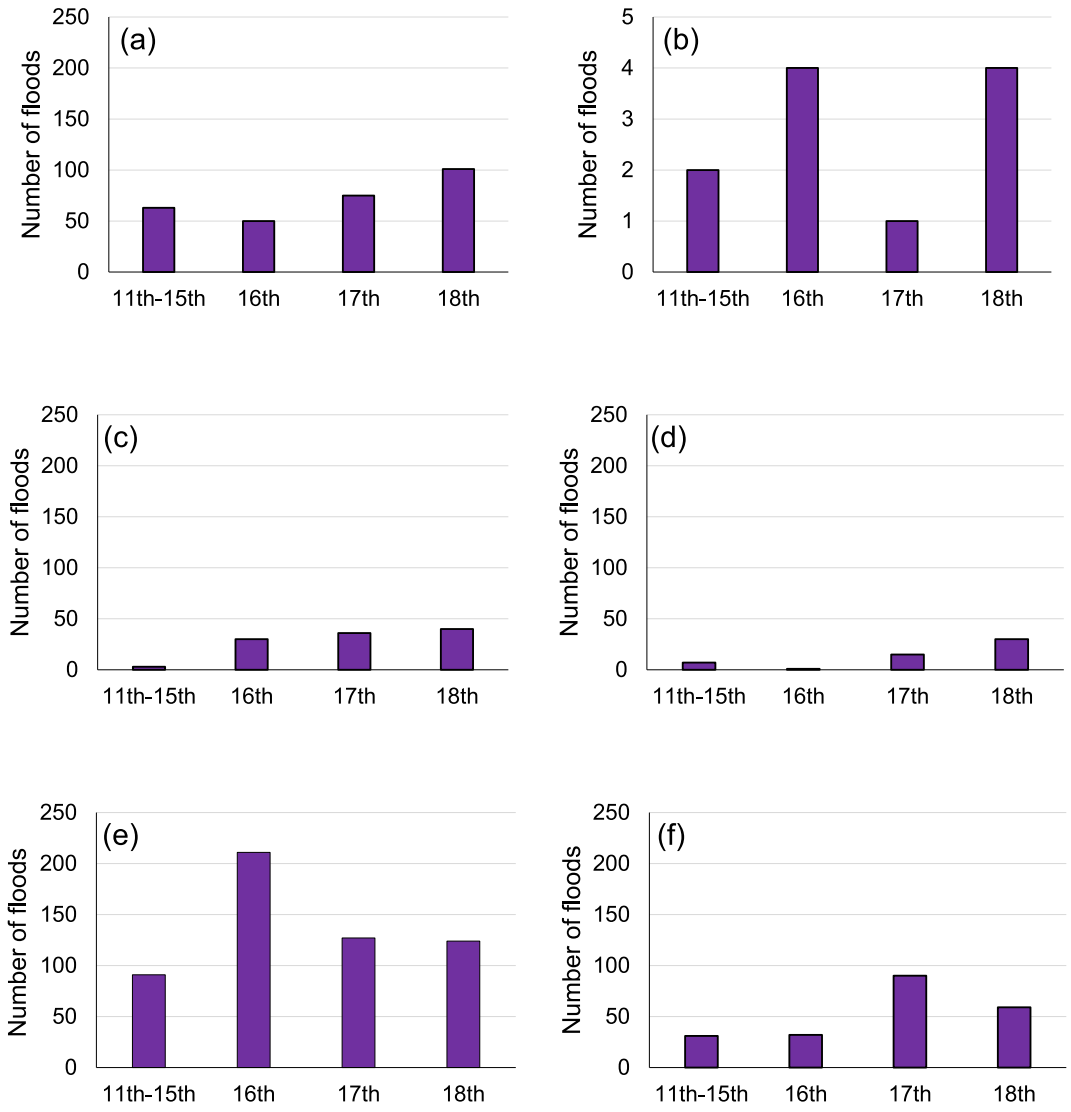


**Fig. 6.** Number of floods in different regions in Poland in different centuries, 1001–1800. (a) Baltic Coast and Pomerania, (b) Masuria-Podlasie, (c) Greater Poland, (d) Masovia, (e) Silesia, (f) Lesser Poland; please note the scale difference in Fig. (b).

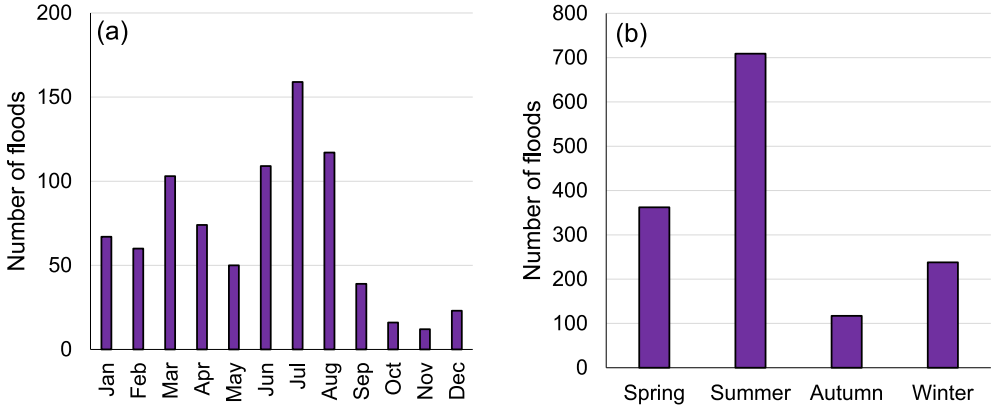


**Fig. 7.** (a) Monthly and (b) seasonal number of floods in Poland in the 11th–18th centuries.

following sites (towns): Wrocław (72), Bolesławiec (59), Gdańsk (52), Kraków (50), Poznań (50), Nysa (34), Toruń (31), Malbork (30), Żytawa (29), Krosno Odrzańskie (25), Mirsk (25), Gubin (24), Warsaw (23), Zgorzelec (23), Kłodzko (22), Gorzów Wielkopolski (20), Złotoryja (18), Pilzno (17), Racibórz (15), Brzeg (14), Gryfów Śląski (14), Legnica (14), Świdwin (12), Gubin and surroundings (11), Lwówek Śląski (11), Słońsk (11) and Szczecin (11).

The issue of changes in flood trends in the era of global warming is a

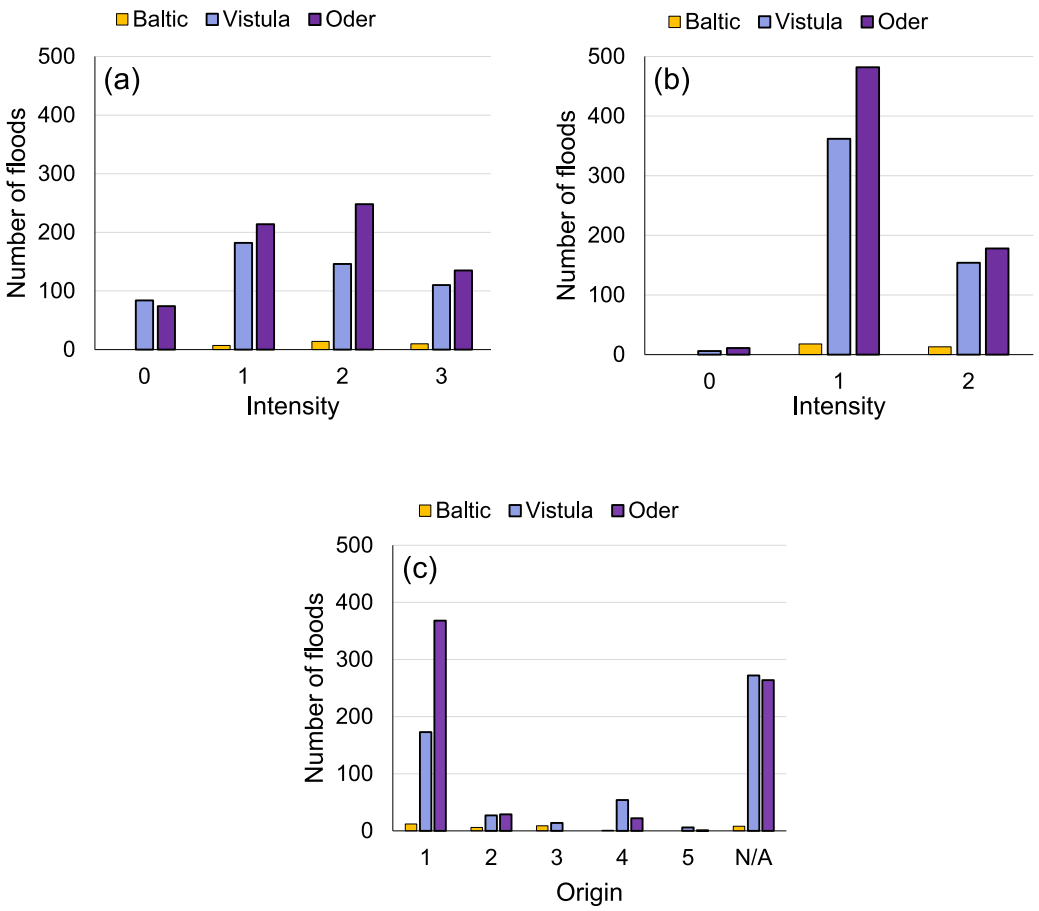


**Fig. 8.** Number of floods in main river basins of Poland in the 11th–18th centuries based on: (a) Method-1, (b) Method-2 and (c) Lambor (1954) origin classification (1: rain and its subtypes, 2: snowmelt, 3: storm, 4: winter, 5: anthropogenic, N/A: no information).

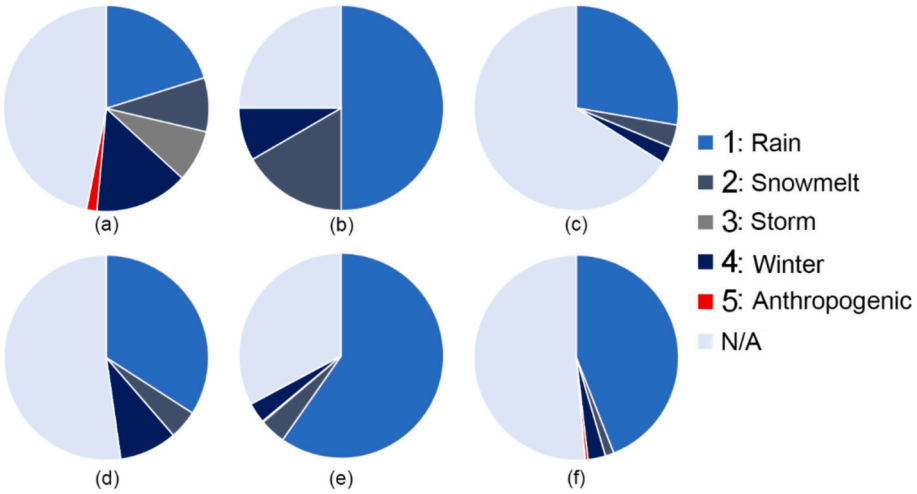


**Fig. 9.** Classification of origin of floods in Poland in the 11th–18th centuries based on Lambor (1954) for: (a) Baltic Coast and Pomerania, (b) Masuria-Podlasie, (c) Greater Poland, (d) Masovia, (e) Silesia, (f) Lesser Poland.

crucial research topic. Having at our disposal a comprehensive and complete database of floods in Poland, we present changes in long-term trends in number of floods (Figs. 13 and 14). 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. Since the 16th century, however, there is no indication of such an obstacle, given that the numbers of both historical sources and weather notes used are comparable among all analyzed centuries (see Fig. 2). Therefore, we present a 30-year moving average trends based on decadal totals for period 1301–2000 (Fig. 13) and flood multi-temporal trend for three periods of 1501–1700, 1601–1800 and 1801–2000 (Fig. 14). As already mentioned, the reader should be aware that the results presented for the 1801–2000 period were achieved based on data available in the

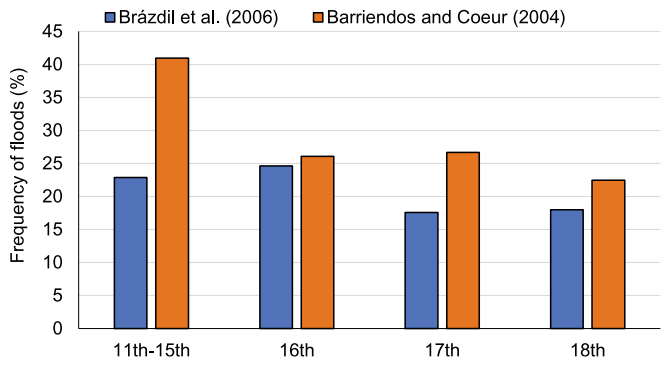


**Fig. 10.** Percentage share of extreme floods ("category 3" as per Brázdil et al., 2006, and "category 2" as per Barriendos and Coeur, 2004) in all floods distinguished for Poland in the study sub-periods.

literature, and therefore the series of floods for the entire period 1501–2000 is probably not homogeneous. 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).

Analysis of the multi-temporal trend presented in Fig. 14 (see tables in the figure) demonstrated that, overall, for the period of 1501–1700 (Fig. 14a) and 1601–1800 (Fig. 14b), positive trends are more numerous than negative trends, whereas for 1801–2000 (Fig. 14c), negative trends are slightly more numerous than positive trends.

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 large 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).

Of all the 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 the changes (including trends) in Poland in the period 1001–1800. For analysis, we extracted floods classified as category 3 by Method-1 and category 2 by Method-2 (Fig. 15).

For both classifications, the results revealed decreasing statistical trends ($p$-value $<0.05$) in the number of extreme flood occurrences in the period 1501–1800. Two 40-year periods can be distinguished that, according to both criteria, have the highest frequency of extreme floods: 1501–1540 and 1651–1690. Interestingly, the exceptionally high number (between 20 and 25) of decadal extreme floods (1561–1570, 1731–1740) did not occur in either of these two periods (see Fig. 15).

## 5. Discussion

Uncertainties and biases in the documentary evidence are a great challenge in reconstructing extreme water phenomena like historical

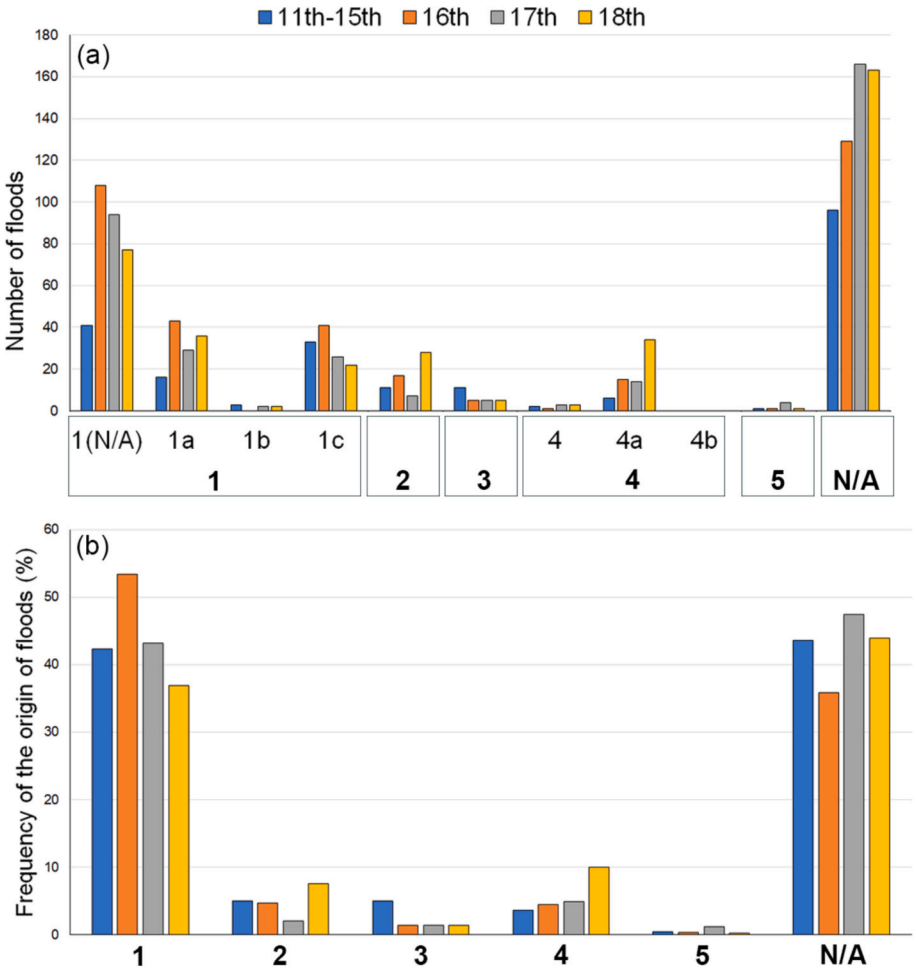


**Fig. 11.** Frequency of type of origin of floods in Poland in the period 1001–1800: (a) number of floods and (b) relative frequency based on Lambor (1954) classification.
(For symbols explanation, see text and Table S5).

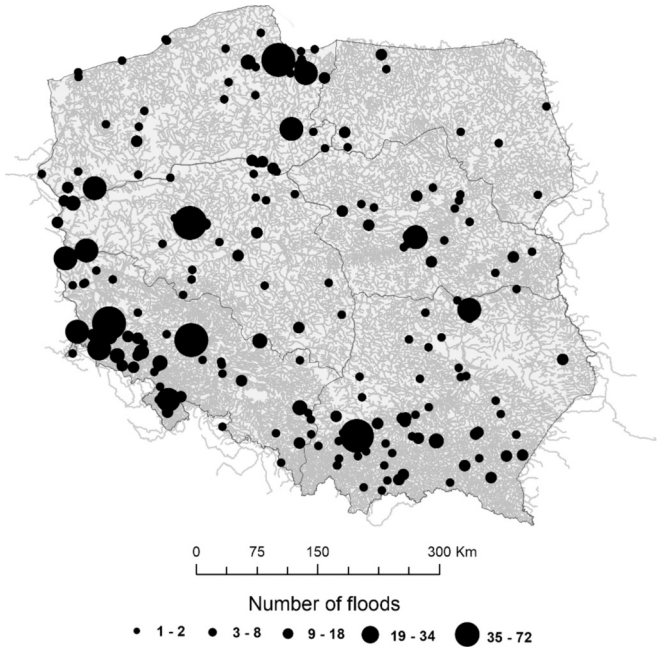


**Fig. 12.** Geographical location of flood occurrences in Poland in the period 1001–1800.

floods (Brázdil et al., 2005b). That is why we tried in this research to eliminate their influence as much as possible, including taking into account the most reliable sources for analysis. However, it should be noted that there are only a few numbers (only 114) of sources available for the medieval period (11th–15th centuries). Of all the sources used for the period 1001–1800 (563), 49 % are weak (mainly from the medieval period), 16 % are moderate, and 36 % are high-quality. In addition, the most abundant sources are secondary literature (298) and published sources (232). The numbers of handwritten-unpublished and database/catalog items are 24 and 9, respectively.

This research presents the most comprehensive and detailed results on the history of floods in Poland in the last millennium, which should significantly enrich the knowledge of this phenomenon in Central Europe. To discuss the results of this study in detail, they are compared against other available information about historical floods in Poland that has been presented in some earlier publications (e.g., Majewski, 1993; Bielański, 1997; Mudelsee et al., 2003; Grześ, 2008; Kasprzak, 2010; Blöschl et al., 2020). Of those, only two (Grześ, 2008; 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 in 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, the assessment of flood occurrences in Poland showed that 1252 floods (522 in the Vistula River basin and 671 in the Oder River basin) occurred in the 11th–18th centuries. The number of floods provided in this research is significantly greater than the numbers given in previous studies (see Table 2, and Table S8). This relation is seen in all distinguished time periods.

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 the literature (Fig. 16). We extracted historical floods for Austria, Czechia and Germany (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 et al., 2011; Blöschl et al., 2020). It is important in considering this comparison to bear in mind the possible existence of some biases due to differences in: (i) the availability and reliability of sources, (ii) the number of rivers in the mentioned countries and (iii) differences in methods used to distinguish floods.

Based on the comparison of the 40-year frequency of floods in Poland, Austria, Czechia and Germany illustrated in Fig. 16, the number of floods was greater in Poland and Germany than in Austria and Czechia. Only in the periods 1601–1640, 1721–1760 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. 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. However, since the 17th century, this trend has disappeared, and fluctuations in the number of floods are a common feature in the studied series of floods. Also evident is that the greatest correspondence between the courses of flood

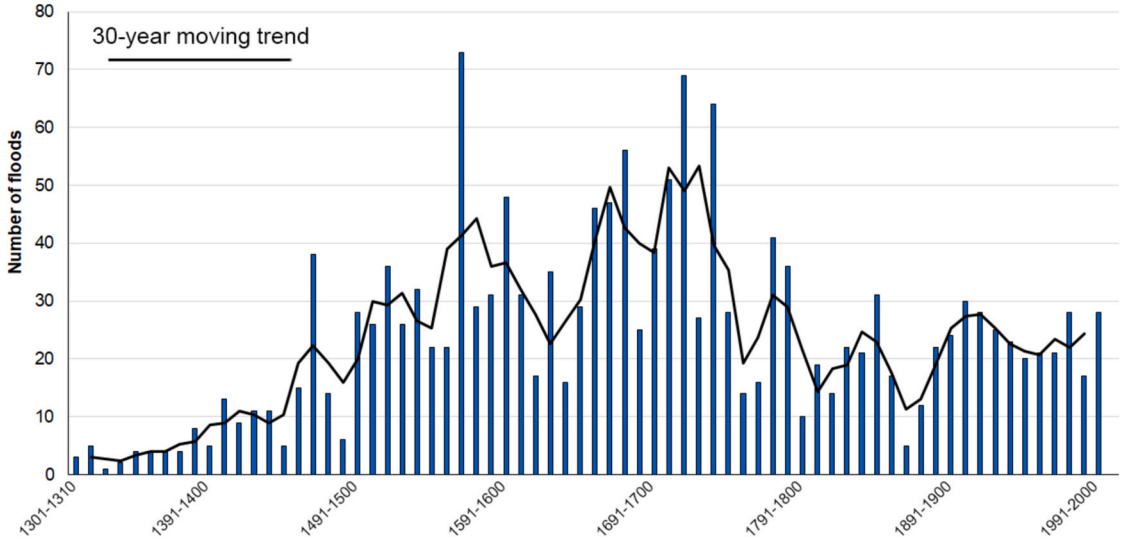


**Fig. 13.** Trends in the number of floods in Poland in the 14th–20th centuries based on 10-year flood totals.

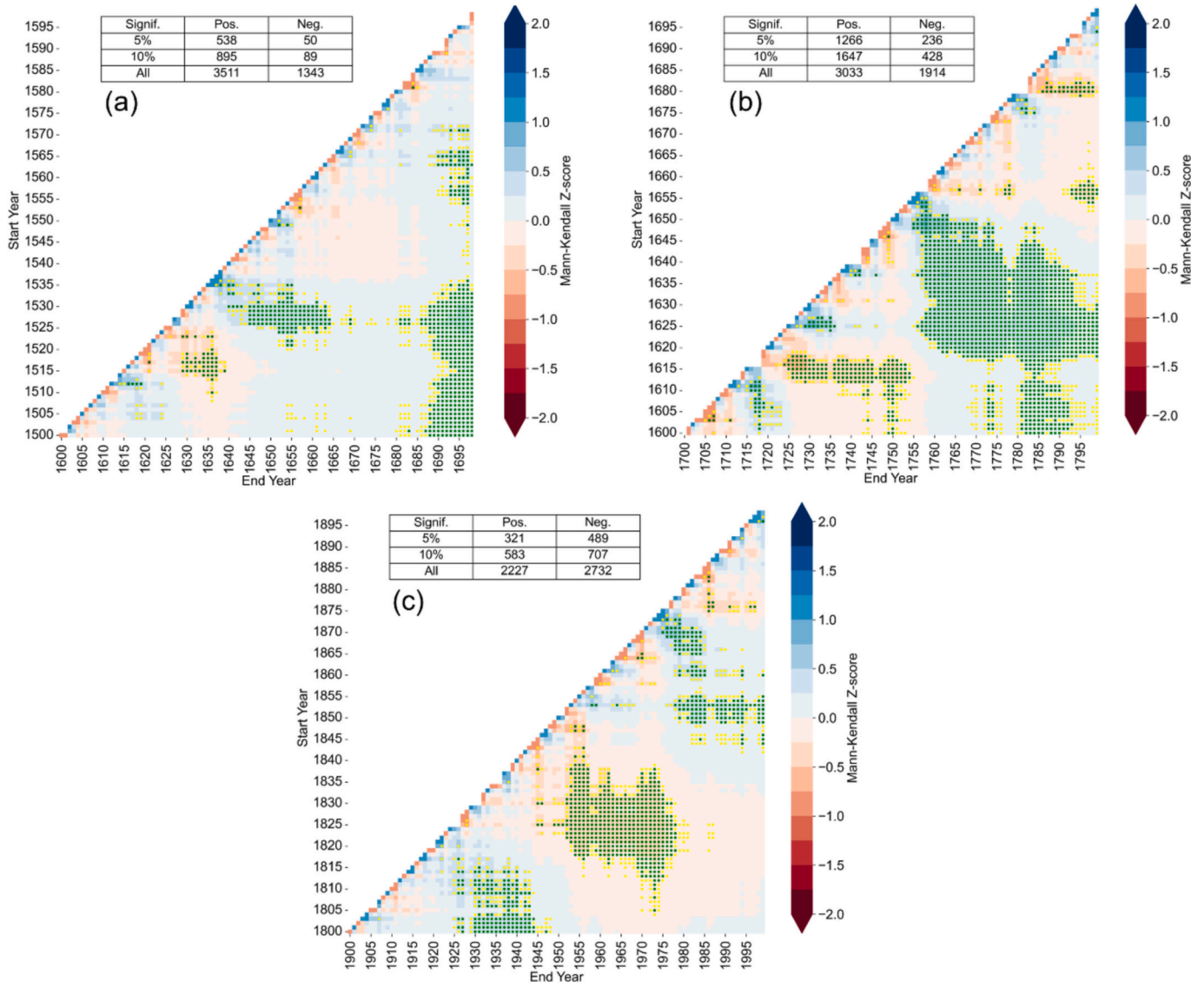


**Fig. 14.** Multi-temporal MK test for floods in Poland in the periods: (a) 1501–1700, (b) 1601–1800 and (c) 1801–2000; Each cell in each matrix presents the result of a trend analysis for starting and ending years.

numbers is between Poland and Germany. The most flood-rich periods in these two areas occurred in the periods 1641–1680 and 1721–1760. In the latter period, Czechia saw its largest number of floods, and there was also a relatively high number in Austria (Fig. 16). The most flood-rich period for all analyzed countries (463 floods) was 1561–1600. In addition, the statistical significance of trends in the number of floods in the mentioned countries was assessed based on the MK test for the 16th–18th centuries (see Fig. S8). The 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 $<0.05$).

The number of floods in Poland, Czechia and Germany for the last 200–year period is depicted in Fig. S9. The data for this figure for all countries were taken from the dataset provided by 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 much greater than in Austria (49, not shown). The main cause of these differences is the differences in the number 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: 1821–1850 (Poland), 1821–1860 (Czechia), and 1831–1870 (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. S9).

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 flood intensities, understanding and distinguishing of extreme floods has 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 S9) (Brázdil et al., 1999; Mudelsee et al., 2003; Brázdil and Kirchner, 2007; Elleder, 2015; Blöschl et al., 2020). It is important to

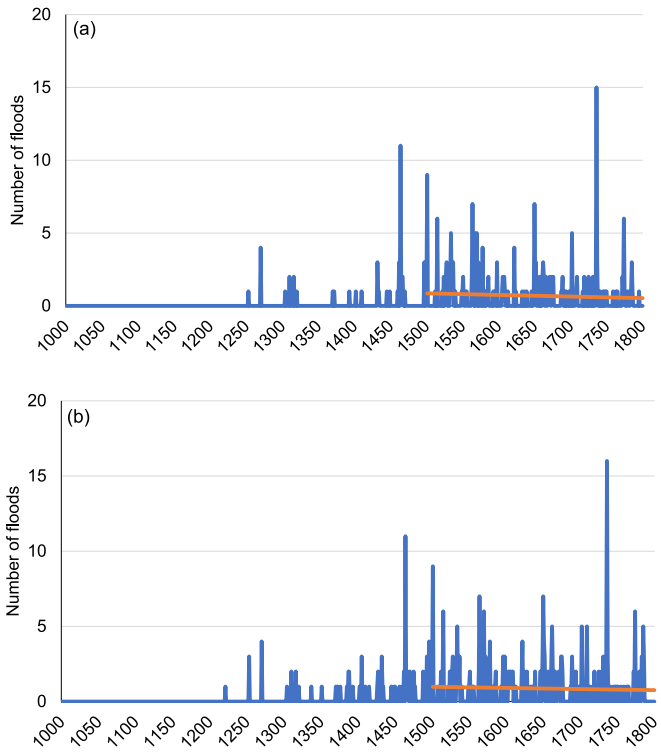


**Fig. 15.** Number of extreme floods in Poland in the 11th–18th centuries in years and their trends for 1501–1800 (orange lines). Key: (a) – "category 3" in Method-1, (b) – "category 2" in Method-2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 in Poland in the 11th–18th centuries. This is significantly lower than the numbers of such floods as identified herein (257 and 347) using the classifications of Brázdil et al. (2006b) (category 3) and Barriendos and Coeur (2004) (category 2) (see Table S9). The number of extreme floods for Czechia and Germany (72 and 119, respectively) was also lower than we found for Poland.

It is appropriate to mention that the results presented in Fig. 10 for the percentage share of extreme floods are generally in line with expectations; 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. A similar conclusion has been presented by Zhong et al. (2024), who analyzed historical written documents for the Alpine catchment.

The analysis of spatial variations of flood occurrences in Poland revealed that a great number of floods in the historical period occurred in Silesia (553, 43 %), while the number was lowest in Masuria-Podlasie (11, ~1 %). The main reasons for this are that historical sources are more numerous 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 11th–18th 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

**Table 2**
Comparison of the 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 |

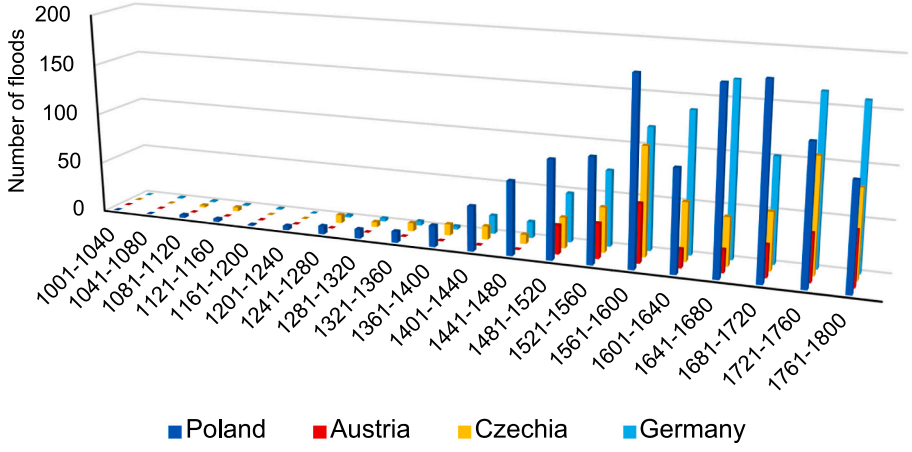


**Fig. 16.** 40-year number of floods in Poland, Austria, Czechia and Germany in the 11th–18th centuries.

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).

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). That work also found that the season with the most common occurrence of floods was summer (41 %), with only a slightly smaller frequency than for Poland.

There is evidence of a global increase in extreme events like floods 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 that century, a high frequency of floods was noted (see Fig. S9a). 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. To date, there is almost no comprehensive study of floods in the last 1000 years on a global scale. There are some regional studies on historical floods, such as in Switzerland (since 1500) (Schmocker-Fackel and Naef, 2010), Dez River, Iran (500-year) (Sharifazari et al., 2023), Europe (1500 CE) (Glaser et al., 2010), Europe (500-year) (Mudelsee et al., 2004; Brázdil et al., 2012; Benito et al., 2015; Blöschl et al., 2020), Yangtze River, China (Huo et al., 2023), Spain (Benito et al., 2003; Barriendos et al., 2019; Sánchez-García et al., 2019). Thus, these case studies (including this study) on a regional scale can provide valuable information on reconstructing historical floods and completing the puzzle of historical floods on a global scale. Therefore, we hope this work somewhat reduces the existing uncertainty in knowledge concerning various aspects of flood frequencies (and origins) in Central Europe, particularly in Poland.

## 6. Conclusions

In the current era of climate change, understanding flood frequency, intensity and origins in the historical past is an important endeavor. Expanding flood records, particularly for the last millennium, can provide valuable information in reconstructing floods and for future prediction of this phenomenon. In the presented study, by developing a comprehensive and unique 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 findings of this research are summarized below:

1. In Poland, there were 1680 floods in the last millennium and 1252 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, according to available sources, were category 2 (“above-average, or supra-regional flood”) after Brázdil et al. (2006) and category 1 (“extraordinary”) after Barriendos and 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[s]).
7. Flood frequencies in Poland exhibited increasing trends in the periods 1501–1800 and 1801–2000 but were statistically significant only in the latter.
8. During the 11th–18th centuries, floods were more frequent in Poland and Germany than in Czechia and Austria.

To conclude, many studies (Kundzewicz et al., 2018; Pińskwar and Choryński, 2021; 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. Thus, as recommendations for future works, it is suggested that the projection of future occurrences of floods for the area of Poland be investigated based on state-of-the-art simulation of climate models.

## CRediT authorship contribution statement

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

## 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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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2025.104706.

## 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.

## References


Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015. Global warming increases the frequency of river floods in Europe. Hydrol. Earth Syst. Sci. 19 (5), 2247–2260.

Alifu, H., Hirabayashi, Y., Imada, Y., Shiogama, H., 2022. Enhancement of river flooding due to global warming. Sci. Rep. 12 (1), 20687.

Ballesteros-Cánovas, J., Czajka, B., Janecka, K., Lempa, M., Kaczka, R., Stoffel, M., 2015. Flash floods in the Tatra Mountain streams: Frequency and triggers. Sci. Total Environ. 511, 639–648.

Ballesteros-Cánovas, J., Spyt, B., Janecka, K., Kaczka, R.J., Stoffel, M., 2016a. Deciphering flood event information from tree-ring data in the Tatra Mountains: implications for hazard assessment. Flood Risk Upper Vistula Basin 257–277.

Ballesteros-Cánovas, J.A., Stoffel, M., Spyt, B., Janecka, K., Kaczka, R.J., Lempa, M., 2016b. Paleoflood discharge reconstruction in Tatra Mountain streams. Geomorphology 272, 92–101.

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

Barriendos, M., Gil-Guirado, S., Pino, D., Tuset, J., Pérez-Morales, A., Alberola, A., Mazón, J., 2019. Climatic and social factors behind the Spanish Mediterranean flood event chronologies from documentary sources (14th–20th centuries). Glob. Planet. Chang. 182, 102997.

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. Chang. 58 (1–2), 171–192.

Benito, G., Brázdil, R., Herget, J., Machado, M.J., 2015. Quantitative historical hydrology in Europe. Hydrol. Earth Syst. Sci. 19 (8), 3517–3539.

Biedroń, I., Bogdańska-Warmuz, R., 2012. Flood 2010—Analysis of Flood losses and Damages in Poland. Gospod. Wodna 4, 147–153.

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

Blöschl, G., Nester, T., Komma, J., Parajka, J., Perdigão, R.A., 2013. The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. Hydrol. Earth Syst. Sci. 17 (12), 5197–5212.

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., 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. Chang. 43 (1), 239–285.

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., Pfister, C., Wanner, H., Storch, H.V., Luterbacher, J., 2005b. Historical climatology in Europe–the state of the art. Clim. Chang. 70, 363–430.

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

Brázdil, R., Řezníčková, L., Valášek, H., Havliček, 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. 56 (3), 468–485.

Brázdil, R., Kundzewicz, Z.W., Benito, G., Demarée, G., Macdonald, N., Roald, L.A., 2012. Historical floods in Europe in the past millennium. In: Kundzewicz, Z.W. (Ed.), Changes in Flood Risk in Europe. IAHS Press, Wallingford, pp. 121–166.

Bryndal, T., 2015. Local flash floods in Central Europe: a case study of Poland. Norwegian J. Geogr. 69 (5), 288–298.

CRED, U., 2015. The human cost of natural disasters 2015: a global perspective. Centre for Research on Epidemiology of Disasters, Université catholique de, 58 pp. Retrieved from. http://cred.be/sites/default/files/The_Human_Cost_of_Natural_Disasters_CRED.pdf.

Czaja, S.W., 2011. Powodzie w dorzeczu górnej. Uniwersytet Śląski, Odry.

Díez-Herrero, A., Mateos, R., Vázquez-Tarrío, D., López-Marcos, A., Brao-González, F., 2024. One catastrophic flood every millennium: Synchronicity of extreme floods and global warm periods in the multi-archive record of the Roman theatre of Guadix (Granada, SE Spain). Glob. Planet. Chang. 233, 104363.

Doocy, S., Daniels, A., Murray, S., Kirsch, T.D., 2013. The human impact of floods: a historical review of events 1980-2009 and systematic literature review. PLoS Curr. 5.

Elleder, L., 2015. Historical changes in frequency of extreme floods in Prague. Hydrol. Earth Syst. Sci. 19 (10), 4307–4315.

Feyen, L., Ciscar Martinez, J.C., Gosling, S., Ibarreta Ruiz, D., Soria Ramirez, A., Dosio, A., Forzieri, G., 2020. Climate Change Impacts and Adaptation in Europe. JRC PESETA IV final report.

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

Ghazi, B., Przybylak, R., Oliński, P., Chorążyczewski, W., Pospieszyńska, A., 2023b. An assessment of flood occurrences in Poland in the 16th century. J. Hydrol. Region. Stud. 50, 101597.

Ghazi, B., Przybylak, R., Pospieszyńska, A., 2023c. Projection of climate change impacts on extreme temperature and precipitation in Central Poland. Sci. Rep. 13 (1), 18772.

Ghazi, B., Przybylak, R., Oliński, P., Targowski, M., Filipiak, J., Pospieszyńska, A., 2024. A comprehensive study of floods in Poland in the 17th–18th centuries. J. Hydrol. Region. Stud. 53, 101796.

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., Stangl, H., Lang, M., 2004. Floods in Central Europe since AD 1300 and their regional context. In: Paper presented at the 175ème session du Comité Scientifique et technique «Etiages et crues extrêmes régionaux en Europe. Perspectives historiques» Congrès de la SHF, Lyon, 28-29 janvier 2004.

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. Chang. 101 (1), 235–256.

Grześ, M., 2008. Historia powodzi na Wiśle w świetle tablic wielkich wód. http://www.wielkawoda.umk.pl/.

Gu, X., Zhang, Q., Li, J., Chen, D., Singh, V.P., Zhang, Y., Yu, H., 2020. Impacts of anthropogenic warming and uneven regional socio-economic development on global river flood risk. J. Hydrol. 590, 125262.

Guerreiro, S.B., Dawson, R.J., Kilsby, C., Lewis, E., Ford, A., 2018. Future heat-waves, droughts and floods in 571 European cities. Environ. Res. Lett. 13 (3), 034009.

Hannaford, J., Buys, G., Stahl, K., Tallaksen, L.M., 2013. The influence of decadal-scale variability on trends in long European streamflow records. Hydrol. Earth Syst. Sci. 17 (7), 2717–2733.

Hannaford, J., Mastrantonas, N., Vesuviano, G., Turner, S., 2021. An updated national-scale assessment of trends in UK peak river flow data: how robust are observed increases in flooding? Hydrol. Res. 52 (3), 699–718.

Huo, R., Chen, H., Li, L., Xu, C.-Y., Li, J., Hong, S., Xia, J., 2023. Flood variability in the upper Yangtze River over the last millennium—Insights from a comparison of climate-hydrological model simulated and reconstruction. Sci. China Earth Sci. 66 (3), 547–567.

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

Kendall, M.G., 1948. Rank Correlation Methods.

Kowalewski, Z., 2006. Powodzie w Polsce-rodzaje, występowanie oraz system ochrony przed ich skutkami. Woda-Środowisko-Obszary Wiejskie 6, 207–220.

Kundzewicz, Z.W., Piniewski, M., Mezghani, A., Okruszko, T., Pińskwar, I., Kardel, I., Benestad, R.E., 2018. Assessment of climate change and associated impact on selected sectors in Poland. Acta Geophys. 66 (6), 1509–1523.

Kundzewicz, Z.W., Januchta-Szostak, A., Nachlik, E., Pińskwar, I., Zaleski, J., 2023. Challenges for flood risk reduction in Poland's changing climate. Water 15 (16), 2912.

Lambor, J., 1954. Klasyfikacja typów powodzi i ich przewidywanie. Gospodarka Wodna 14 (4), 129–131.

Lee, D., Ward, P., Block, P., 2018. Attribution of large-scale climate patterns to seasonal peak-flow and prospects for prediction globally. Water Resour. Res. 54 (2), 916–938.

Lehmkuhl, F., Schüttrumpf, H., Schwarzbauer, J., Brüll, C., Dietze, M., Letmathe, P., Hollert, H., 2022. Assessment of the 2021 summer flood in Central Europe. Environ. Sci. Eur. 34 (1), 107.

Liu, J., Feng, S., Gu, X., Zhang, Y., Beck, H.E., Zhang, J., Yan, S., 2022. Global changes in floods and their drivers. J. Hydrol. 614, 128553.

Lorenc, H., 2012. *M*aksymalne prędkości wiatru w Polsce. Instytut Meteorologii i Gospodarki Wodnej–Państwowy Instytut Badawczy.

Majewski, A., 1993. Kronika Powodzi w delcie Wisły,[w:] Uwarunkowania przyrodnicze i społeczno-ekonomiczne zagospodarowania dolnej Wisły, red. Z. Churski, Instytut Geografii, Uniwersytet Mikołaja Kopernika, Toruń.

Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 245–259.

Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J.E., Gattke, C., 2022. A multi-disciplinary analysis of the exceptional flood event of July 2021 in Central Europe. Part 1: event description and analysis. Nat. Hazards Earth Syst. Sci. Discuss. 2022, 1–44.

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. Atmos. 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.

Pawłowski, B., 2003. Piętrzenia zatorowe na dolnej Wiśle w świetle blizn lodowych na drzewach poziomu zalewowego, praca doktorska, maszynopis IG UMK. IG UMK, Toruń.

Pińskwar, I., Choryński, A., 2021. Projections of precipitation changes in Poland. In: Climate Change in Poland: Past, Present, Future. Springer, pp. 529–544.

Rohde, M.M., 2023. Floods and droughts are intensifying globally. Nat. Water 1 (3), 226–227.

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,. Cologne/Weimar/Vienna, pp. 56–61.

Sánchez-García, C., Schulte, L., Carvalho, F., Peña, J.C., 2019. A 500-year flood history of the arid environments of southeastern Spain. The case of the Almanzora River. Glob. Planet. Chang. 181, 102987.
Schmocker-Fackel, P., Naef, F., 2010. Changes in flood frequencies in Switzerland since 1500. Hydrol. Earth Syst. Sci. 14 (8), 1581–1594.
Schulte, L., Schillereff, D., Santisteban, J.I., 2019. Pluridisciplinary analysis and multi-archive reconstruction of paleofloods: Societal demand, challenges and progress. Glob. Planet. Chang. 177, 225–238.
Sharifazari, S., Palmer, J.G., Higgins, P.A., Rao, M.P., Johnson, F., Turney, C.S., Andersen, M., 2023. 500-year reconstruction of Dez River discharge in southwestern Iran from tree rings. J. Hydrol. 624, 129895.
Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L.M., Van Lanen, H.A.J., Sauquet, E., Jódar, J., 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrol. Earth Syst. Sci. 14 (12), 2367–2382.
Starkel, L., 2001. Extreme rainfalls and river floods in Europe during the last millennium. Geogr. Pol. 74 (2), 69–80.
Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Sci. Rep. 10 (1), 1–10.
Tanoue, M., Hirabayashi, Y., Ikeuchi, H., 2016. Global-scale river flood vulnerability in the last 50 years. Sci. Rep. 6 (1), 36021.
Tsiokanos, A., Rutten, M., van der Ent, R.J., Uijlenhoet, R., 2023. Flood drivers and trends: a case study of the Geul River Catchment (the Netherlands) over the past half century. Hydrol. Earth Syst. Sci. Discuss. 2023, 1–24.
Zhong, Y., Ballesteros-Cánovas, J.A., Favillier, A., Corona, C., Zenhäusern, G., Manchado, A.M.T., Qie, J., 2024. Historical flood reconstruction in a torrential alpine catchment and its implication for flood hazard assessments. J. Hydrol. 629, 130547.