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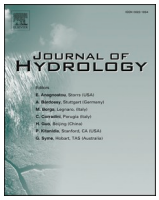

Research papers

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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

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

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

2. Study area, data, and methods

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

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

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

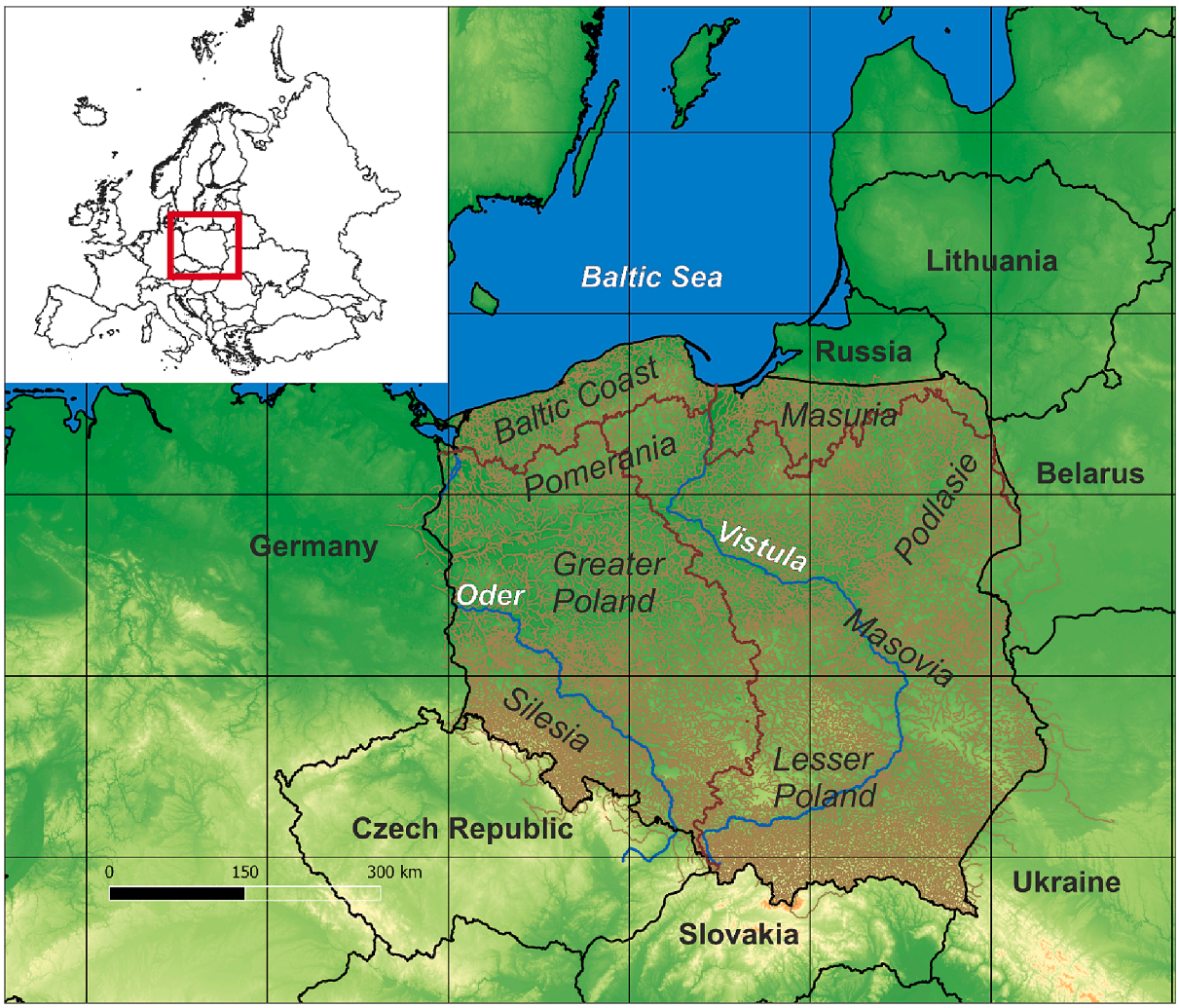

Fig. 1. Location of study area, including main rivers and geographical regions.

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

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

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

The results were elaborated in four main stages:

(1) the creation of a database of all flood events in Poland from the 11th to 15th centuries based on all available documentary evidence. The constructed database contains, besides a simple list of floods, important additional information such as: location, time and duration, original description, name of source, quality of sources (for more details see https://doi.org/10.18150/WD18XJ);

(2) a two-step indexation of flood categories using classifications proposed by Brázdil et al. (2006) and Barriendos and Coeur (2004) (for details see Tables 1 and 2). The first step of indexation involved all authors of the present paper referring to all sources containing information about the occurrence of floods in the study area from 11th to 15th centuries and each independently using the flood descriptions to perform a classification. For some floods, however, more than one source of data exists. Therefore, in the second step all such cases were carefully analyzed by the entire team and a final indexation was proposed taking particular account of the more reliable sources;

(3) the estimation of the origins of floods by the method propose by Lambor (1954) and modified by us (for details see Table 3);

(4) a basic statistical analysis of flood occurrence, including their intensity and origin.

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

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

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

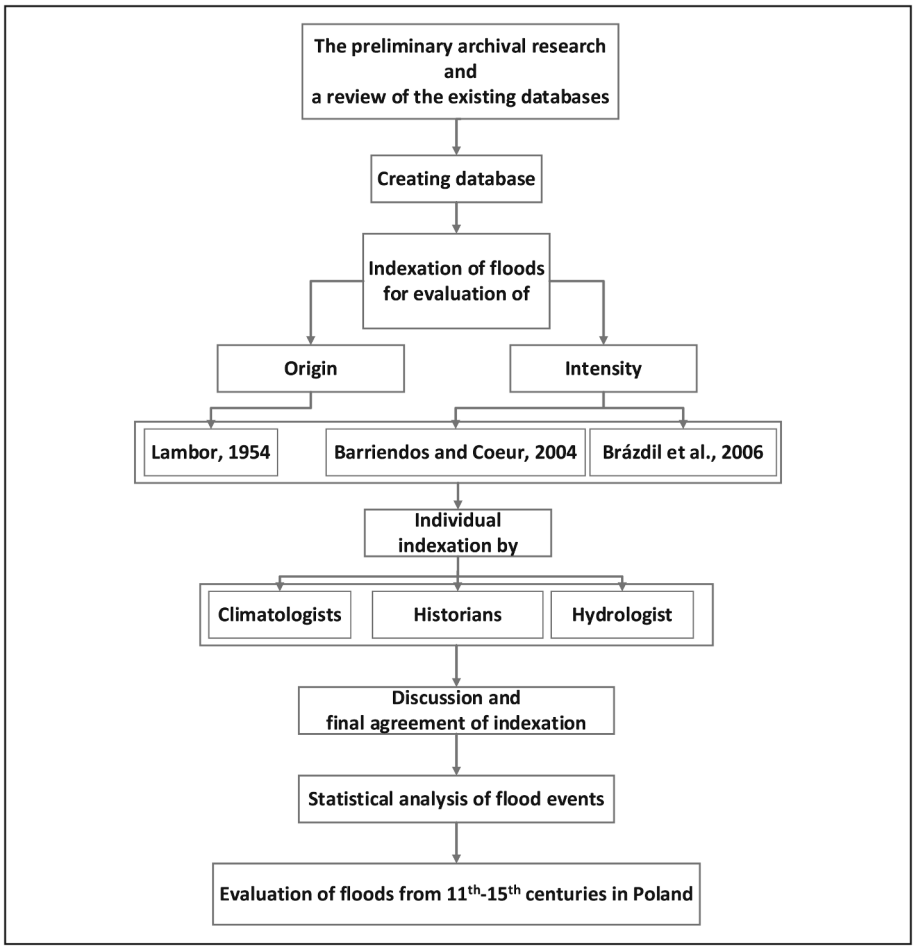

Fig. 2. Data elaboration procedure.

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

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

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

3. Results

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

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

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

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

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

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

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

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

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

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

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

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

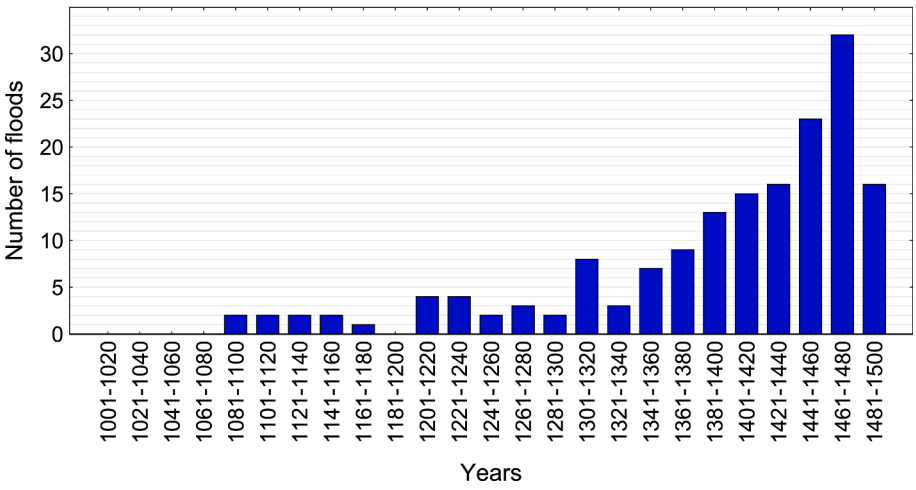

Fig. 3. Numbers of floods in 20-year periods in Poland from 1001 to 1500.

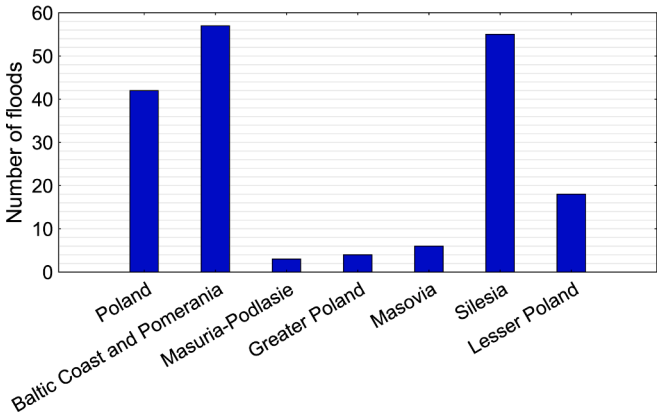

Fig. 4. Number of floods in various geographical regions of Poland during 11th–15th centuries.

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

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

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

Another very important research issue we undertook was to estimate

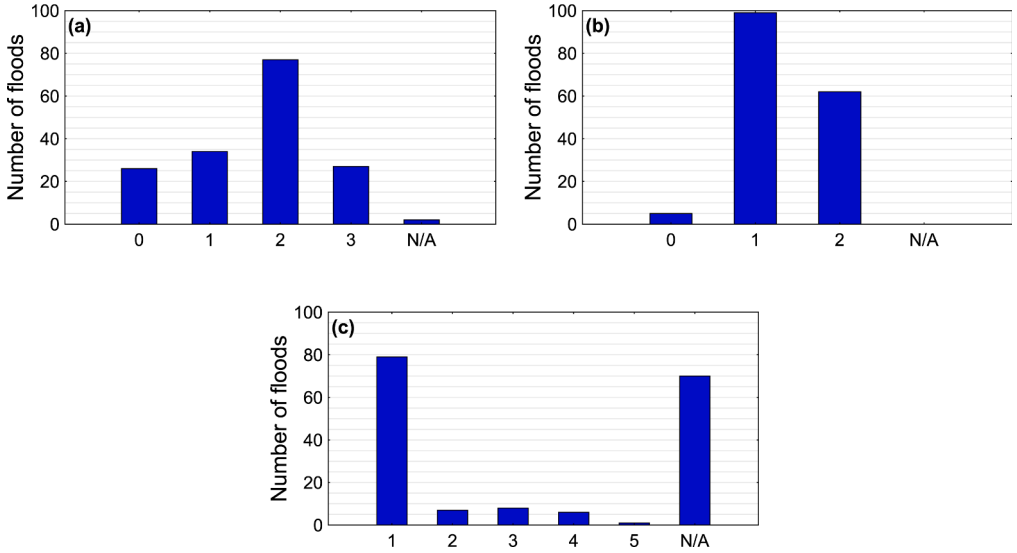

Fig. 5. Total number of different categories of flood intensities in Poland in the period 1001–1500 based on classifications of (a) Brázdil et al. (2006) and (b) Barriendos and Coeur (2004); and (c) categories of origin of floods based on Lambor (1954). Key: N/A means information is not available.

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

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

4. Discussion

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

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

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

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

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

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

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

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

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

Table 6 (*continued*)

Century	Current research (Poland)	Mudelsee et al. (2003) (Germany) Elbe	Brázdil et al. (2005) (Czech Republic) Vltava, **Ohře**, *Elbe*	Kiss (2019) (Hungary)
	(2), 1496 (2), 1497 (2), 1500 (2)			1496 (2), 1498, 1499 (3), 1500

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

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

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

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

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

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

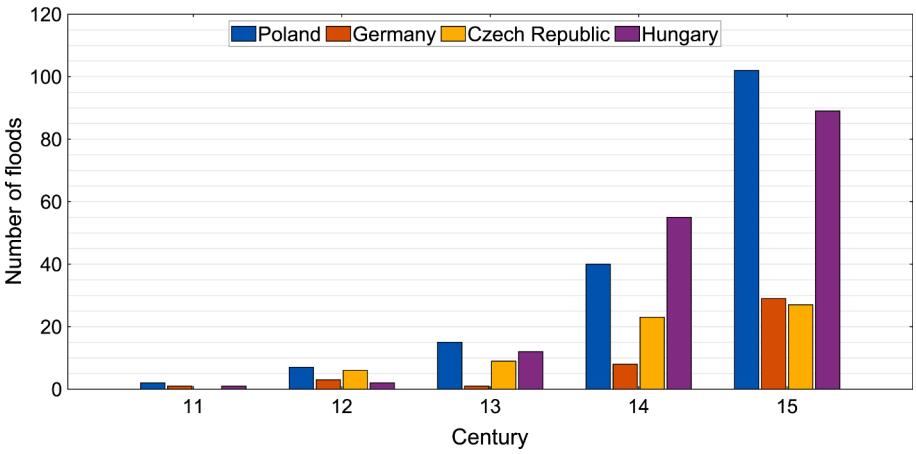

Fig. 6. Number of floods in Poland, Germany, Czech Republic and Hungary, 1001–1500.

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

5. Conclusions and final remarks

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

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

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

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

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

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Data Availability Statement

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

Significance statement:

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

Appendix A. Supplementary data

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

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