Editor Initial Decision: Reconsider after major revisions (11 May 2015) by Prof. Günter Blöschl
Comments to the Author:
Dear authors

Thank you for submitting this manuscript to HESS. Based on the review comments and on my own examination of the manuscript, I find that your manuscript requires substantial revisions to address the issues that have been raised through the review process.

While the paper contains interesting results, I believe that some of the review comments have not been fully addressed in your response. I strongly recommend that your address them fully in your revised manuscript which will be sent out for rereview. Please also write a reply to each of the editorial comments below:

Figure 3 needs to be changed as it is misleading. As it is now it suggests that the flood frequency has increased immensely in the past millennium. More likely this is an artefact of the data collection. The figure needs to be redrawn and the caption completed to make it crystal clear that the main pattern shown is observation bias.

Answer:

- The applied method is a common tool within historical geography concerning flood time series (cf. e.g. . Glaser 2008, Glaser & Stangel 2003b, Böhm & Wetzel 2006, Sturm et al. 2001, Schmoecker-Fackel & Naef 2010, …). To meet the requirements data of former fig. 3, now fig. 4, has been z-transformed. So the weak data density until the beginning of the 16th century is clearly denoted by values beneath of the zero line. Therewith the under- and over-representative availability of data in a statistical way should be taken in account. Due to good data availability with beginning of the 16th century I do not agree that fig. 4 shows an observation bias in general. Weak data density before 16th century has additional been textual emphasized. To consider the increasing data density a polynomial function has been integrated.

Information is missing in the paper which needs to be supplied in the revision. For example, information needs to be given on what rivers individual floods refer to (eg. by colouring the floods shown by the river, giving percentages for each decade etc). It also needs to be stated whether the raw data used refer to individual locations or river reaches. How was a flood wave along a river counted, multiple times or once, and what was the threshold to decide among these alternatives?

Answer:

- Paper has been supplemented about all single time series, compare “new” fig. 3.

- Chapter ‘Methods’ has been supplement with following paragraphs:

For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

- To reveal the flood sensitivity of the entire Bavarian Foreland, all flood events of the outer alpine region have been merged into one overall time series. The highest classification according to damage reports has been counted whereas local events caused by i.e. flash-floods have not been counted. Hence only mesoscale hydrological events have been incorporated into the present analysis.

In a similar vein, a much more detailed and accurate description of the sources is needed. Please include exact references to the main sources (rather than simply the source type). As you are probably aware, scientific papers need to be repeatable, and without accurate information it will not be able for the reader to trace where the information came from which, however, is a requirement for publication.

Answer:

- Chapter 'Database' has been supplement with a more detailed description of the used data and organization of the database IBT.

- Yes, I'm aware of good scientific/academic praxis and the necessity of repeatability! As samples for related papers I've listed two of them (see below) with following insight: Compared with the present paper these papers have one similarity: The description of the used data corresponds approximately with mine: brief and succinctly. Please compare:

  Schmocker-Fackel & Naef (2010): Changes in flood frequencies in Switzerland since 1500. – In: Hydrol. Earth Syst. Sci.. 1582-1594.

  Jacobeit, J., Wanner, H., Koslowski, G. & M. Gudd (1999): European surface pressure patterns for months with outstanding climatic anomalies during the sixteenth century. – In: Climatic Change 43. 201-221.
- Of course I can prove the data source of each individual flood. But the intention of the current paper was not the discussion of a dataset but the data analysis. Each individual flood has been taken out of a multitude of different sources. A release for the data of Bavarian Foreland under 'tambora.org' should be soon realized. Data of former HISKLID is under tambora.org already accessible. I can't see the reasonableness of listing the sources of 1825 flood events in the recent paper. For example the compilation of Weikinn includes more than 23.000 entries and all floods concerning the Bavarian Foreland have been re-investigated. That means all data in Weikinn with reference

to the investigation area have been back trailed. But I can't see the scientific necessity to list all of the back trailed chronicles because the reference Weikinn is already given.

- In general references for main sources are given. But to meet the requirements the continuous text has been supplemented, see below:

To highlight some selected sources the 'Chroniken deutscher Städte' (Chronicles of German Cities 1862 –1968) focused to the city of Augsburg upon river Lech and the publications of Stahleder (1995 – 2005) for the city of Munich upon river Isar will be introduced briefly. Within the 'Chroniken deutscher Städte' the chronicles about the city of Augsburg must be highlighted especially. Inside the superior 'Chroniken deutscher Städte' the history of Augsburg is organized into 'Die Chroniken der schwäbischen Städte' (The chronicles of Swabian Cities, Augsburg 1865 – 1929). For the second oldest city of Germany in total seven volumes are existent including substantial information about river Lech floods. Within these seven volumes the following chronicles have been edited: Volume 1 (1865) contains the 'Augsburger Anonyme Chronik' from 1368 – 1406 with proceeding until 1447, the chronicle by Erhard Wahraus from 1126 – 1445 with supplements until 1462 and the chronicle from foundation of the city of Augsburg until 1469. Volume 2 (1866) contains the chronicle by Burkard Zink from 1368 – 1468. Volume 3 (1892) contains the chronicle by Hector Mülich 1348 – 1487 and the anonymous chronicle from 991 – 1483. Volume 4 (1894) includes the chronicle from oldest time of the city until 1536 plus proceeding of the chronicle by Hector Mülich. Volume 5 (1896) contains 'Cronica newer geschichten' by Wilhelm Rem 1512 – 1527, Johannes Franks ‚Augsburger Annalen' from 1430 until 1462 and supplements concerning the chronicle by Clemens Sender. Volume 6 (1906) contains the chronicle of Georg Preu from 1512 until 1537. Volume 7 (1917) contains two chronicles by apparitor Paul Hektor Mair. Volume 8 contains 'The Diary of Paul Hektor Mair' from 1560 – 1563 and the second chronicle by Paul Hektor Mair 1547 – 1565. And volume 9 contains the weaver chronicle by Clemens Jäger from 955 – 1545.

Helmuth Stahleder, ex-alternate director of the 'Stadtarchiv München' (city archive Munich) evaluated all data within the city archive of Munich to compensate the miss-ing of history of Munich within 'Chroniken deutscher Städte'. Foundations of this compilation among others are original documents, calculations of city treasurer and yearbooks. Result of the longstanding investigation was the 'Chronik der Stadt Mün-chen' in three volumes concerning the history of Munich between the years 1157 – 1818. A multitude of flood events along river Isar are recorded within 'Chronik der Stadt München'. Each record is furnished with a related city archive reference.

A more technical point is what is referred to as a "non critical approach". Full justification is needed about how realistic this approach is and why it is preferred over the more usual critical approach, in particular the gain in accuracy over the critical approach.

Answer:

- The main argument of the NCA is to expand the data base. The paragraph has been retyped, see below:

  To expand the data basis as wide as possible we have applied a methodical practice we have named "Non Critical Approach" (NCA) (cf. Böhm 2011). The NCA is a procedure especially designed for extraordinary hydrological events. Within the range of historical climatic data, flood information has an exceptional position. Common threads connecting available flood information are damages which have led to burdens on former neighbors. The main argument for the NCA is based on the reasonable assumption that historical flood reports - due to the particular burdens - contain more objective information than other descriptions of climatic events. In the center of this approach stands the tradition of the gist of 'flood event' trough time. Starting point of this approach was the fundamental question if anonymous sources in general may be regarded as verified sources (cf. e.g. Augsburger Anonyme Chronik von 1368 bis 1406. In: Die Chroniken der schwäbischen Städte. Augsburg, Band 1. Leipzig 1865). According to a rigorous interpretation of source criticism all of the (environmental-related) information of this source would have to be discarded. Based on the NCA we use all available sources and information about flood events of the outer-alpine river sections concerning the period of documentary evidences. Avoiding classical source criticism the NCA contributes to increase acquisition of information and reduces the thinning of relevant information during times of limited flood documentation. This approach minimizes the loss of original written records concerning historical flood information due to anthropogenic or natural calamities.
  To verify the NCA various stress tests have been trialed. Glaser et al. (2002) state that a spatial criterion for the distribution pattern of weather-climatic causes can be implied by sufficient data density. Within the scope of the NCA a spatiotemporal/synoptical criterion has been consulted to verify historical data. All superior flood events of the Bavarian Foreland have been visualized by spatiotemporal flood distribution pattern with the assistance of geographic information systems. Therefore plausible (spatiotemporal/synoptical) evidence for the validity of flood information can be adduced. Further confirmation was given by cross-comparison with verified records, e.g. HISKLID (cf. Böhm 2011).

  Environmental psychological aspects provide a further backing for the NCA. In brief damaging flood events have an exceptional position in cultural history and the transfer of information through time based on primal fear still contains the gist. A more de-tailed description of the NCA is to be found in Böhm (2011).

The flood rich periods, apparently, are derived from fitting a polynomial to the flood frequencies per 31 years. This looks like an arbitrary method and needs justification. Why a polynomial? Why 31 years? The fracture point analysis is based on a similar averaging window so does not provide much extra information.

Answer resp. changes to the issue ‘fitting a polynomial’:

- This method does not claim precision for the beginning and the end of the defined periods but compared to a multitude of other methods and due to the changing data density over time it is the highest-performance method. Different methodical approaches with the aid of quantiles as medians or percentiles could not achieve satisfactory definitions for the generated time series and its comparability. The determined periods should come over as the results of a sensitivity analysis.

Answer resp. changes to ‘Why 31 years?’:

- In order to be able to properly understand the long-term development of flood events in the Bavarian Foreland, z-transformed 31-year running flood frequencies have been calculated in several studies (e. g. Glaser 2008, Glaser & Stangel 2003b, Böhm & Wetzel 2006, Sturm et al. 2001, Schmoecker-Fackel & Naef 2010). The 31-year time step is derived from the standard reference period of the World Meteorological Or-ganization. This time segment is an established tool to identify the linkage of climatic coherence of time series and exhibits significant changes in flood frequencies. Alt-hough this measure results in a comparatively poor filtration effect it still meets the needs of various geoscientific approaches to define climatological phases (Schönwiese 1992).
- 31-year running frequencies and polynomial have been chosen for graphical presentation in a qualitative way. To raise the discussion up to a quantitative level the spectrum of methods has been supplemented about the t-test analysis.

Finally, the English needs improvement.

Revised paper was proof-read by professional.

In highlighting these points, it is not my intention to discount other elements of the reviews.

Dr Macdonald (Referee)
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Overall comment: This is interesting paper addressing a pertinent question, how have floods changed over a long timeframe. The application of the Alps Foreland to this study is appropriate and provides considerable insight into the challenges faced when using 'long' river flow series augmented by historical records, this represents a challenge though in the many and diverse factors that have influenced changes in the 'natural' flow to the river, though these are discussed. The paper provides a clear explanation of the value of long records, the importance of their consideration and the fact that few studies have identified trends in many of these long flood series and attempts
C2311
to link these to the generating mechanisms. The identification of the flood rich phases needs to be more clearly stated and explained (section 4), with more justification as to why methods are employed. The discussion would benefit from being expanded further to include a short section on how these results relate to those from previous studies, are similar or different flood rich periods being identified, this would provide a greater interest to readers from other regions beyond the Alps – a similar point can be made to the introduction, which could be made of wider appeal by including regions outside Central Europe.

> Answer:
> The summarized main queries in the introduction of the referees comment will be answered on corresponding positions, see below.

The reference list included within this paper is good. An annotated copy of the manuscript is supplied containing a list of suggested amendments that the authors may wish to consider. These contain suggested re-phasing and minor queries.

Key points requiring attention:

p.4, l.12-16, you need to explain very careful what you mean by multiple river records being merged, as a single event can manifest in different ways on, between or along a river system, with the same event resulting in different magnitude floods at different places.

> Answer:
> The aim of the current paper is a superordinate spatial unite based on recent administrative borders under consideration of climatic parameters. Only the flood events of the middle reaches and tail waters have been consulted. In general the investigation area has due to its geomorphological shape been divided in one inner- and outer-alpine region. Only the outer alpine region (see fig. 1 dashed line) has been considered for the present paper. Basically the highest classification due to damage reports has been counted, local events caused by for example flashfloods have not been counted. Due to the description of damage and climatic/hydrologic parameters as well as the geomorphological parameters of the outer alpine region in combination with reconstructed weather patterns on the basis of the date base IBT local events can be almost absolute excluded.

Changes ‘Introduction’:
The merging of the single time series should reveal the flood-susceptibility of a superordinate spatial unit based on recent administrative borders under consideration of climatic parameters. In the methods’ section the merging of the single time series is more elaborately described. Single flood events as well as quantification of flood events do not stand in the limelight of the current paper. The time line of the flood history of the Bavarian Foreland includes 584 individual flood events (see methods’ section).
Changes ‘Methods’:
For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

p.5, l.4, you need to be more specific about what you mean, ‘anthropogenic encroachments’.

Changes:
…the riverbeds have deepened themselves. About 1850 Bavarian Administration started systematically riverbed corrections in order to prevent floods and protect infrastructure like railways and roads and to support agriculture in to the fertile plains and meadows due to growing population. In Fig. 2a one can see due to the results of gauge measurements the beginning of the anthropogenic encroachments, in the current figure starting around 1860. Gauges neutral points have not been changed, staff gauges have been prolonged into the negative measurement range. These circumstances affect hydrological interpretations concerning the EIP…

p.9, l. 20-, you need to explain why you have used the polynomial function rather than another function, a reference to past example would be easy solution, or a couple of lines of justification.

Changes:
The determinations of flood-rich and flood–poor periods are based on a polynomial function of the 5th degree for the running flood frequencies (see red graph in Figure 4). Using this function the inhomogeneity of the number of cases could best be con-fronted. Different databases and data densities (e. g. 14th/15th century - turn of the 15th to 16th century - beginning of the instrumental period) were thus considered as far as possible. This method does not claim precision for the beginning and the end of the defined periods but compared to a multitude of other methods and due to the changing data density over time it is the highest-performance method. Different methodical approaches with the aid of quantiles as medians or percentiles could not achieve satisfactory definitions for the generated time series and its comparability. The determined periods should come over as the results of a sensitivity analysis. The fixing of the threshold based on a polynomial function of the fifth degree coincides with the fracture points of the t-test analyses (cf. Fig. 4), so the method is provided by statistical measure.

Fig.3 starts with a very low polynomial score which shows the
early phase as flood rich (similarly the end as poor), but this line is being forced to fit through the data and may need careful consideration at the ends.

Answer:

- Regarding only the floods per annum (cf. grey columns) depicts (small) accumulation of flood events, please compare new fig. 3 and its itemized time series. This period is provided by qualitative conclusions in different papers as well. References on the climatic circumstances are given e.g.by Wanner et al. 2000, Lamb 1982. But due to bidden brevity and weak data density the circumstances have been shortened and concentrated. But former Fig. 3 has been redrawn (cf. 'new' fig. 4). To regard weak data density befor 16th century data of fig. 4, has been z-transformed. So the weak data density until the beginning of the 16th century is clearly denoted by values beneath of zero line. Therewith the under- and over-representative availability of data in a statistical way should be taken in account. Weak data density before 16th century has additional been textual emphasized. In general the polynomial function has been integrated to consider the increasing data density.

- Changes:

  …in Figure 4. A further qualitative confirmation for particular climatic circumstances during that period is provided by Lamb (1982).

Why do you use 31years - justify?

Answer:

The applied method is a common tool within historical geography concerning flood time series (cf. e.g. . Glaser 2008, Glaser & Stangel 2003b, Böhm & Wetzel 2006, Sturm et al. 2001, Schmoecker-Fackel & Naef 2010, …). 31-year sliding frequencies' have been chosen due to comparability to a multitude of other works using the same time step. The 31-year time step is derived from the standard reference period of the World Meteorological Organization (WMO). It's a proper tool to identify the linkage of climatic coherences out of time series.

Changes:

In order to be able to properly understand the long-term development of flood events in the Bavarian Foreland, z-transformed 31-year running flood frequencies have been calculated in several studies (e. g. Glaser 2008, Glaser & Stangel 2003b, Böhm & Wetzel 2006, Sturm et al. 2001, Schmoecker-Fackel & Naef 2010). The 31-year time step is derived from the standard reference period of the World Meteorological Or-ganization. This time segment is an established tool to identify the linkage of climatic coherence of time series and exhibits significant changes in flood frequencies. Alt-hough this measure results in a comparatively poor filtration effect it still meets the needs of various geoscientific approaches to define climatological phases (Schönwiese 1992).

p.10, ll-5, I think you need to explain more clearly what the fractures are being used to indicate, as they reflect periods of change in a series, and not increased numbers
C2312
of flood events, you might consider modifying the title of Fig. 4, to more clearly reflect this.

Changes:

… time series (cf. Glaser & Stangl 2003b). The fracture points reveal differences between the means of sliding flood frequencies. The differences, shown by estimators above the threshold are expected to detect significant coherences between superior framework conditions like variations of large-scale atmospheric circulation and consequential variability of flood-poor and –rich periods.

Modified title of former fig. 4 now fig.5:
Differences of sliding means by 31-year running t-test estimator of flood frequencies of the Bavarian Foreland, threshold value for the two-sided t-test is 2.00 (see red line). Grey bars label flood-rich periods #1 to #9.

p.10, l.14, you need to clearly show where the flood rich phases are on Fig.3, insert your grey boxes onto this figure – possibly above the curves/columns.

Changes: Flood rich periods according to the grey boxes in Fig. 4 supplemented, see below:

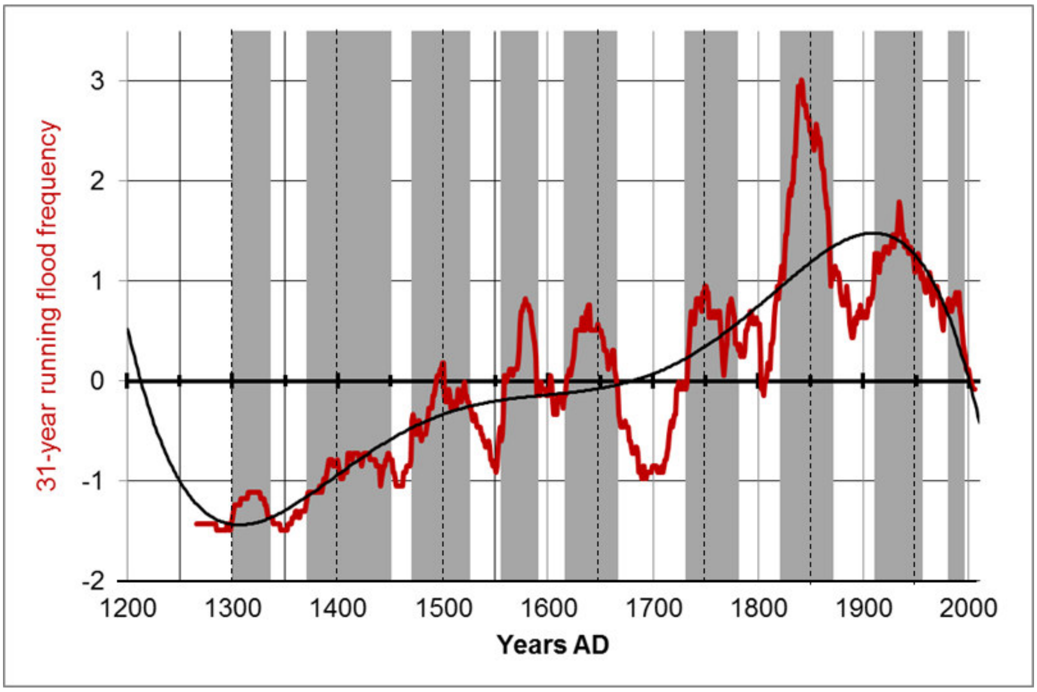

Fig. 4: 31-year running z-transformed flood frequencies of the Bavarian Foreland. Grey bars label flood-rich periods #1 to #9

p.10, l. 12-14, you need to check the numbering of the figures and the discussion associated with them in the text, I think there are a couple of places for example where you discuss flood rich phases in relation to Fig. 3 – these can be deduced but are not clearly shown, see above point. There are a number of places where Fig. numbers need reviewing.

Answer: Relations have been fixed for final revised paper

p.10, l.17, The consideration given to increasing frequency of records and the potential implications on flood frequency needs further assessment, can you devise an approach which allows for the increasing frequency of accounts to be compensated into your estimation of frequency - I appreciate the polynomial has been used to identify the phases but then running meas of events are used in Fig. 5. I suspect this in part explains the increased frequencies post 1700.

Answer:

Running means have been the fundament for the polynomial as well as for the curves in former fig. 5 now fig. 6. To ensure the compatibility between the running mean of floods and sunspots depicted in Fig. 6, the values of both time series have been z-transformed.

p.13, l.5, you ask the reader to compare Fig.5 to Wanner et al., (2000), I think you need to be more explicit here, what do I need to compare in Wanner to Fig.5?

Answer:

Wanner et al. reconstructed the movement of glacier tongues of selected Switzerland glaciers, i.a. of the Aletsch Glacier. Under consideration of the delay of glacier movement a correlation of mass balance and flood-rich period # 5 can be derived. This coherence is already listed in chapter 5.6.

p.13, l.8, you may wish to have a look at the flood rich phase termination (phases 4 and 5), as at the end of phases the 31-yr flood frequency line is below 0, can this be reassessed?

Answer:

Values below 0 are caused by z-transformed values (z-scores) of the running means.

Discussion section: Can you link the findings of this work to those from other areas of Europe, UK, Spain, Scandinavia, Czech Republic, are the findings similar, are different patterns emerging? Why might that be?

Answer:
Result Chapter will be expanded about a comparison in a central European context. A further comparison is interesting concern but can't be realized at

the moment. In context of the current HESS special issue a paper by Kiss et al. regarding this concern is in preparation. The main-author contributes to that review article.

Changes:
The flood frequencies of the Bavarian Foreland in confrontation with selected flood frequencies of Central Europe

This confrontation is limited to the period between 1500 and 1900. The limitation is founded due to weak data density in general before 1500 and due to a multitude of anthropogenic overprints of the river systems around the beginning of the 20th century. The comparison will be limited to the Lower Rhine and Middle Rhine (cf. Glaser 2008) and Vlatva (an Elbe tributary) and the Czech Elbe itself (cf. Brazdil 1998). The confrontation is depicted in table 4. Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Similarities for all time series can be particularly highlighted for the second half of the 16th century. In general an unexpected similarity can be stranded between the time series Bavarian Foreland and the Lower Rhine, except the years 1790 until 1819. Good accordance between the Bavarian Foreland can be revealed for the first and seventh and eighth decade of the 16th century. During the 17th century only the sixth decade shows good accordance. Again good accordance can be highlighted for the end of the 18th and beginning of the 19th century. Reasons for this variable behavior are founded in the variability of general synopsis and resulting weather conditions. In that context the above mentioned NAO is playing a vital role. For a further understanding of the variability between the confronted time series meteorological aspects must be consulted.

Table 4. Confrontation of selected flood frequencies. Lower Rhine (RHl), Middle Rhine (RHm), Czech Elbe (ELBcz), Vlatava (VLA) and Bavarian Foreland (BF). Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Data altered according to Glaser (2008) and Brazdil (1998).

	RHl	RHm	BF	ELBcz	VLA	
1500						1500
1510						1510
1520						1520
1530						1530
1540						1540
1550						1550
1560						1560
1570						1570
1580						1580
1590						1590
1600						1600
1610						1610
1620						1620
1630						1630
1640						1640
1650						1650
1660						1660
1670						1670
1680						1680
1690						1690
1700						1700
1710						1710
1720						1720
1730						1730
1740						1740
1750						1750
1760						1760
1770						1770
1780						1780
1790						1790
1800						1800
1810						1810
1820						1820
1830						1830
1840						1840
1850						1850
1860						1860
1870						1870
1880						1880
1890						1890
1900						1900

Fig. 1 – rephrase text beneath caption

Modification:

Fig. 1: Investigation area “Bavarian Foreland” is bordered by the rivers Iller, Danube, Inn/Salzach and the Alpine border (dashed line). Red spots are locating outstanding historical locations and gauges.

Figures 5,6 and 7: can one of these lines be dashed and ticks provided on x-axis so we can see where the years relate too as the grey blocks obscure the lines on the
C2313
figure.

Revisions have been implemented

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/11/C2311/2014/hessd-11-C2311-2014-supplement.pdf

Revised paper was proof-read and due to major revisions partial retyped but considers the mentioned suggestion.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 7409, 2014.
C2314

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Received and published: 21 November 2014
General evaluation: This paper presents an analysis and interpretation of the documentary sources on floods for Bavarian Alps foreland. Whereas in Bavaria, the systematic records of flood levels go back to 1821, using the documentary sources, authors succeeded in extension of the flood analysis to the 13th century. I consider the paper as very interesting and valuable.
Specific comments and points to be addressed:
1. I strongly suggest the authors to include the overall summary of used data. How many flood events (without specifica-
C5228
tion of locality) were recorded during the examined period?

Answer:

In the database "IBT" are more than 32.000 records organized. For the investigation area above 1800 single records could be collected. All other records are temporal linked to Bavarian Foreland flood events as a European climatic frame to understand meteorological and climatological geneses for floods into the investigation area. The database of this paper resp. for Fig. 4 are above 1800 different flood records which could be assigned to 584 independent flood events.

Changes & supplements in 'Database':
The IBT itself contains more than 32.000 flood events within (Central-) Europe, all of them with a temporal relationship to the 584 independent flood events identified for the Bavarian Foreland (see below). …

… In Table 3 all flood events used for the merged time series "flood frequencies of the Bavarian Foreland" (cf. fig. 4) are listed. The data for the time series Bavarian Foreland is derived from 1825 different flood records in total which can be assigned to 584 independent flood events.

Table 3. Synoptic table of data basis 'flood frequencies Bavarian Foreland'. Columns a to c contain all outer-alpine flood events of documentary evidences until 1880, segmented after intensity levels. Columns d to e contain all floods derived from instrumental periods until 2008 for one representative gauge per river. EIP = Early Instrumental Period, MIP = Modern Instrumental Period.

River	a) Level 1	b) Level 2	c) Level 3	d) EIP/MIP level 2	e) EIP/MIP level 3
Iller	32	53	15	45	13
Wertach	37	79	20	66	16
Lech	101	159	80	78	38
Isar	88	101	29	55	18
Salzach	154	113	78	56	22
Inn	79	82	63	48	7

I mean the flood event asspecified on example of flood event of 1501 (7418/ pp. 10–15).

Changes in 'Methods' concerning the counting of contemporaneous floods like in 1501:

For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

2. The authors should stress in how many sites (profiles – being either hydrological sites or sites mentioned in chronicles) were the flood events recorded in the IBT database. It is not clear if these are the 9 sites presented by Fig. 1 (Kempten (Iller), Augsburg, Landsberg- (river Lech), Munich, Landshut (Isar), Innsbruck, Wasserburg (Inn), Salzburg, Burghausen (Salzach)?

Answer:

Fig. 1 depicts the most important historical sites concerning historical records. The sites are also depicted to express the spatial location of the investigation area. For the time series Bavarian Foreland written evidences of the middle reaches and tail waters have been consulted. For the EIP only one gauge was considered. For EIP please compare p. 7414, line 4 following, Discussion Paper.

Changes 'Database':
Due to the approach explained below every written evidence of the middle reaches and tail waters has been considered.

If it is the case, it should be explicitly mentioned in the text. Or are these above mentioned sites just the most important places were the floods were mentioned, or are these just places with water gauges?

Answer:

Beside the historical importance, all sites are historical/recent gauge stations. But only one representative gauge station per river was used for the time series. Please compare p. 7415 l. 5, Discussion Paper.

Changes: Text beneath caption of Fig. 1 has been rephrased
Fig. 1: Investigation area. The Bavarian Foreland is bordered by the rivers Iller, Danube, Inn/Salzach and the Alpine border (dashed line). Red spots are locating outstanding historical locations and gauges.

This should be clarified in the text. If there are more important places relevant for the topic, they should be described and adequately marked in Fig. 1. 3.
The authors should provide more detailed information on the documentary data on floods at disposal for the above profiles – particularly interesting is the time span of the data and count of the documentary sources.

Answer:

Please compare Chapter 3 "Database". This chapter has been supplemented a brief description of the used data. Main aim of the current paper was not a detailed discussion of the used data but the flood vulnerability of a superordinate spatial unite as function of climatic parameters.

4. Bohm (2006) provided the analysis of flood frequencies separately for Munich and Augsburg, similarly Schmocker et al. (2010) analysed the flood series separately for Switzerland. In this paper, in contrast, the data is merged and analysed jointly. Why? What is the reason?

Answer:

The aim of the recent paper was a superordinate spatial unite based on recent administrative borders under consideration of climatic parameters. The merging of the single time series should reveal the flood-vulnerability of the investigation area. But itemized time series of the rivers Iller (A), Wertach (B), Lech (C), Isar (D), Salzach (E) and Inn (F) have been supplemented, cf. new fig. 3.

Is there any benefit for merging the data? And how about the limitations? With respect to the point 1. of my review, it is desirable to clarify what are these flood events presented in the graphs showing 31-year standardized frequency. How were the flood events selected – what criteria did the authors select – please, specify in the text.

Answer:

On page 7416 line 7 following (Discussion Paper), the selection criteria are justified with an approach called NCA (supplemented in the revised version). In general the selection criteria are based on damage reports.

Changes 'Introductio':
… have been merged for one overall time series. The merging of the single time series should reveal the flood-sensitivity of a superordinate spatial unite based on recent administrative borders under consideration of climatic parameters. Single flood events as well as quantifications of flood events do not stand in the limelight of the current paper. The timeline of the flood history …

Changes 'Methods':
For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

5. The authors should explain the acronym "EIP" time series.

Answer:

EIP means early instrumental period. Please compare page 7412 line 9

6. I suggest the authors to compare their results with the results of similar analyses published for Switzerland, and particularly for the Czech Republic, where significant similarity in flood frequency can be anticipated.

Changes:

The flood frequencies of the Bavarian Foreland in confrontation with selected flood frequencies of Central Europe

This confrontation is limited to the period between 1500 and 1900. The limitation is founded due to weak data density in general before 1500 and due to a multitude of anthropogenic overprints of the river systems around the beginning of the 20th century. The comparison will be limited to the Lower Rhine and Middle Rhine (cf. Glaser 2008) and Vlatva (an Elbe tributary) and the Czech Elbe itself (cf. Brazdil 1998). The confrontation is depicted in table 4. Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Similarities for all time series can be particularly highlighted for the second half of the 16th century. In general an unexpected similarity can be stranded between the time series Bavarian Foreland and the Lower Rhine, except the years 1790 until 1819. Good accordance between the Bavarian Foreland can be revealed for the first and seventh and eighth decade of the 16th century. During the 17th century only the sixth decade shows good accordance. Again good accordance can be highlighted for the end of the 18th and beginning of the 19th century. Reasons for this variable behavior are founded in the variability of general synopsis and resulting weather conditions. In that context the above mentioned NAO is playing a vital role. For a further understanding of the variability between the confronted time series meteorological aspects must be consulted.

Table 4. Confrontation of selected flood frequencies. Lower Rhine (RHl), Middle Rhine (RHm), Czech Elbe (ELBcz), Vlatava (VLA) and Bavarian Foreland (BF). Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Data altered according to Glaser (2008) and Brazdil (1998).

7. The authors should clearly denote the flood rich periods (the area above the polynomial function) in Fig. 3 – some appropriate tool for accentuation of the area should be used (shades of grey, #1-#9, colour).

Changes:

Flood rich periods according to the grey boxes in Fig. 4 supplemented, see below:

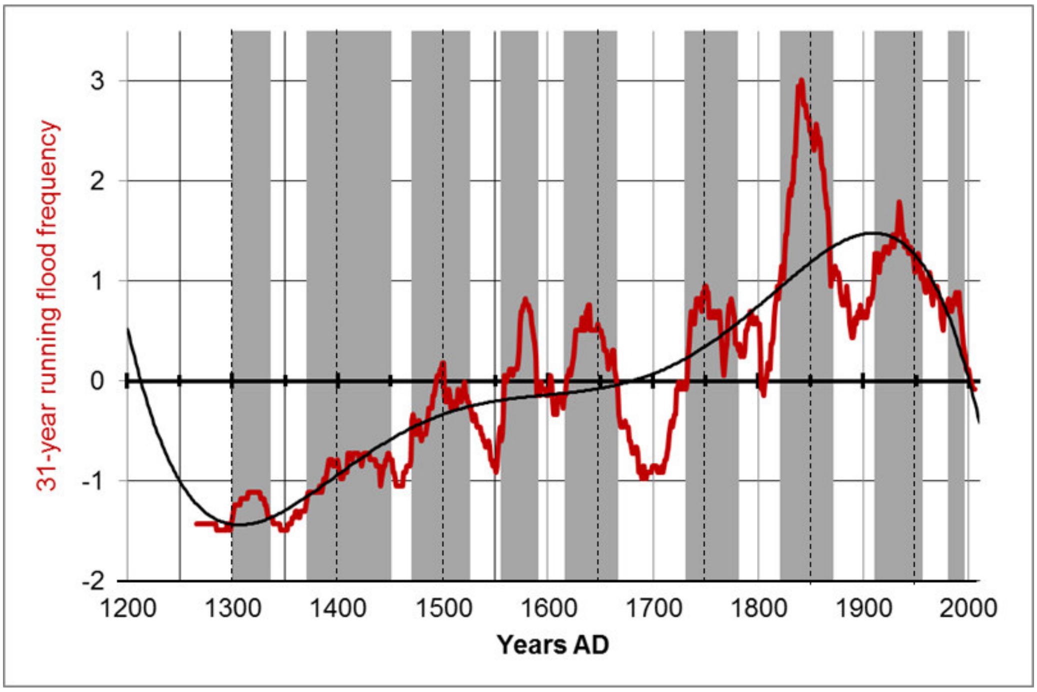

Fig. 3: 31-year running flood frequencies of the Bavarian Foreland. Right ordinate: black columns show the annual flood frequencies, grey bars label flood-rich periods #1 to #9

Minor corrections â c Fig. 2 a, b – monthly maxima should rather be presented by the bar chart – it would be more transparent

Style has been changed to suggestion of referee#3

â
c Fig. 3 – the x-axis should begin in the
year of 1250, the polynomial approximation is pointless â

Starting the x-axes with 1200 should punctuate the weak data density before 14th century

´c 7416 - Fig. 4a – do the
C5229
authors mean Fig. 2a? â
c 7425 com-pared

Numbering has been changed

Answer: Minor revisions have been fixed for final revised paper

Interactive comment on
"Flood history of the Bavarian Alpine Foreland since the late Middle Ages in the context of internal and external climate forcing factors" by
O. Böhm et al.
Anonymous Referee #3
Received and published: 28 November 2014 The comment was uploaded in the form of a supplement: http://www.hydrol-earth-syst-sci-discuss.net/11/C5360/2014/hessd-11-C5360-2014- supplement.pdf
Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 7409, 2014.
C5360
Referee Comment for Hydrology and Earth System Sciences
GENERAL COMMENTS
This manuscript is produced in a framework of European research on historica floods. Past years of systematic efforts of data collection are producing first exploratory results. Present manuscript show a primary overview about different climatic forcing factors explaining variability on flood frequency and seasonality. One of obejctives is a better characterization of present uncertainty in central Europe on this natural risk. Historical climatology is presented as a right especiality to collect historical information on that, generating and analizing data
(qualitative, quantitative, instrumental), obtaining results to improve knowledge of climatic and risk temporal patterns of low frequency. Results are very interesting. Considering floods as a compex phenomena, with different factors at different time scale, including human factors, regional detailed approaches give us to scientific community partial but solid results to reduce uncertainties on this matter. Many techniques or methods for historical information treatment results new and interesting to be applied in other researches. Classification by indices is more or less usual, but corrections of variation on river bed depth result a concept very important for a better management of historical information of "context" when historical floods must be reconstructed more carefully as be possible.

SPECIFIC COMMENTS
-- Section 1. Introduction. P. 7412. Lines 5-10...
Authors give details of documentary sources researched for flood database. One question about it: for region under study, there are documentary sources available from local authorities (City Councils or similar)?

> Answer:
> The database is divided. Descriptive data have been investigated in archives, chronicles, libraries, compilations and already existing databases like the HISKLID (ger.: Historische Klimadatenbank Deutschland by Rüdiger Glaser). The data of the EIP (early instrumental Period) from 1826 on could be investigated, maybe saved at the former archive of the former Bavarian Water Authority. Data basis of the EIP are worksheets with water level details in daily resolution. In the revised version chapter 'Database' has been supplemented with more detailed information.

From my experience, these sources are enoughly correct and reliable to obtain information on flood events in historical time. Any comment about this potential documentary source would be appreciated.

Answer:
Main aim of the current paper was not a detailed discussion of the used data but the flood vulnerability of a superordinate spatial unite as function of climatic parameters. To meet the requirements the revised version chapter 'Database' has been supplemented with more detailed information.

-- Section 3. Database. Authors mention clearly origin of information (biblio. references, databases...) collected for flood database. But is not easy to appreciate what is dimension and

Answer:
Revised version chapter 'Database' has been supplemented with more detailed information. Chapter 'Results has been supplemented about the itemized time series of the rivers Iller (A), Wertach (B), Lech (C), Isar (D), Salzach (E) and Inn (F), cf. new fig. 3.

Changes:

In Table 3 all flood events used for the merged time series "flood frequencies of the Bavarian Foreland" (cf. fig. 3) are listed. The time series is derived from 1825 different flood records in total which could be assigned to 584 independent flood events.

Table 3. Synoptic table of data basis 'flood frequencies Bavarian Foreland'. Columns a-c contains all outer alpine flood events of documentary evidences until 1880 segmented after intensity levels. Columns d-e contains all floods derived from instrumental periods until 2008 for one representative gauge per river. EIP = Early Instrumental Period, MIP = Modern Instrumental Period.

River	a) Level 1	b) Level 2	c) Level 3	d) EIP/MIP level 2	e) EIP/MIP level 3
Iller	32	53	15	45	13
Wertach	37	79	20	66	16
Lech	101	159	80	78	38
Isar	88	101	29	55	18
Salzach	154	113	78	56	22
Inn	79	82	63	48	7

It could give opportunity to compare with similar approaches from other regions or basins.

-- P. 7417. Lines 5-20. Organization of information about flood events is excellent. This is not a criticism, but this comment is needed to be highlighted. At present, with improvement and increasing information on historical floods, researchers involved can work with criteria suggested by authors: all information must be organized in flood events, considering all flood records or cases. One flood record can be unique to know about one flood event. But other flood events may consist of a large number of flood records. A detailed analysis is needed to identify flood events, avoiding biases or wrong interpretations of data.

Answer:

Due to the data base IBT meteorological perimeters for the flood events under consideration of recent distribution of precipitation and weather conditions have been considered to identify "one" flood event. In the database are more than 18.000 flood records organized. For the investigation area above 1800 single records could be collected. All other records are temporal linked to Bavarian Foreland flood events as a European climatic frame to understand meteorological and climatological geneses for floods into the investigation area.

Changes in chapter 'Database':

To expand the data basis as wide as possible we have applied a methodical practice we have named "Non Critical Approach" (NCA) (cf. Böhm 2011). The NCA is a pro-cedure especially designed for extraordinary hydrological events. Within the range of historical climatic data, flood information has an exceptional position. Common threads connecting available flood information are damages which have led to bur-dens on former neighbors. The main argument for the NCA is based on the reasonable assumption that historical flood reports - due to the particular burdens - contain more objective information than other descriptions of climatic events. In the center of this approach stands the tradition of the gist of 'flood event' trough time. Starting point of this approach was the fundamental question if anonymous sources in general may be regarded as verified sources (cf. e.g. Augsburger Anonyme Chronik von 1368 bis 1406. In: Die Chroniken der schwäbischen Städte. Augsburg, Band 1. Leipzig 1865). According to a rigorous interpretation of source criticism all of the (environmental-related) information of this source would have to be discarded. Based on the NCA we use all available sources and information about flood events of the outer-alpine river sections concerning the period of documentary evidences. Avoiding classical source criticism the NCA contributes to increase acquisition of information and reduces the thinning of relevant information during times of limited flood documentation. This approach minimizes the loss of original written records concerning historical flood information due to anthropogenic or natural calamities.

To verify the NCA various stress tests have been trialed. Glaser et al. (2002) state that a spatial criterion for the distribution pattern of weather-climatic causes can be implied by sufficient data density. Within the scope of the NCA a spatiotemporal/synoptical criterion has been consulted to verify historical data. All superior flood events of the Bavarian Foreland have been visualized by spatiotemporal flood distribution pattern with the assistance of geographic information systems. Therefore plausible (spatiotemporal/synoptical) evidence for the validity of flood information can be adduced. Further confirmation was given by cross-comparison with verified records, e.g. HISKLID (cf. Böhm 2011).

Environmental psychological aspects provide a further backing for the NCA. In brief damaging flood events have an exceptional position in cultural history and the transfer of information through time based on primal fear still contains the gist. A more de-tailed description of the NCA is to be found in Böhm (2011).

Changes in chapter ‘Methods’:

For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

-- P. 7424. Lines 3-5. Authors find good coherence between solar sunspots and flood frequency variability. It seems evident that cold periods record higher frequency of flood events. At least for any specific cases. I recognize for example for my study area strong coincidence for Wolf Minimum, not for Maunder Minimum. Considering complexity of climatic system, and having data for other similar period at historical scale, authors could give any comment about relation between this forcing factor and flood events? For example, both processes don't show temporal inercy or delete. How could affect so quickly solar sunspot to flood frequencies? Or any atmospheric mechanism is producing any direct effect?

Answer:
The question about the physical links between flood frequencies and the variation of sunspot resp. the transfer through the atmospheric layers can’t be answered at the moment. Author is working on a DFG proposal (German Research Foundation) which will contribute to solve this question.

-- P. 7425. Lines 8-9. Description of NAO climatic pattern. For public not focused on climatology, more detailed description of NAO pattern would be grateful. This is a journal of hydrology. For example, details about regions affected by NAO patterns, seasonality, atmospheric processes involved. Any basic reference on NAO pattern would be also positive to make easy acess to more details.

Changes:
Due to oscillations of barometric pressure between the so called Island cyclone and Azores anticyclone weather conditions of the investigated area can be affected in various manners.

-- P. 7438. Figure 5. All flood chronologies are plotted as an unique flood data series. It means a regional indices is created. Please, authors must define how this index is created. Is weighted? It use all events?, only level 3? all series? Please, more information is needed.

Answer:
The aim of the current paper is a superordinate spatial unite based on recent administrative borders under consideration of climatic parameters. Only the flood events of the middle reaches and tail waters have been consulted. Due to the created approach NCA all events have been considered.

Modification: Chapter ‘Database’ and chapter ‘Methods’ have been supplemented to meet the requirements.

TECHNICAL CORRECTIONS

-- P. 7416. Line 24. Reference to "Figure 4a" has any problem. It's not available as a figure. May be "Figure 2a" ??

Numbering has been changed

-- P. 7425. Line 6. "com-pared" by "compared"

Revised paper was proof-read

-- P. 7435. Figure 2a and 2b. Style of this figure must be changed. Saturation of black dots produce too visual noise for a correct comprehension of figure.

Style has been changed

Answer: Technical corrections have been fixed for final revised paper

Anonymous Referee #4
Received and published: 2 December 2014
General comments:
The authors aimed to provide an analysis on the flood history of the Bavarian Alpine Foreland, based on the flood series of 6 rivers, from the beginning of the 14th century. The paper is well structured, the aim is clear and well defined. The topic has high relevance, the length of the investigated series is rather impressive. I recommend the paper, after revising and extending certain parts, for publication in HESS. However, I have a number of major or minor suggestions, and I think a major revision of the paper is necessary before publication.

C5419
Specific comments:
1) In the title of the paper the authors suggests that the paper is about the "flood history" of the Bavarian Alpine Foreland. However, the content of the paper is exclusively related to the identification and analysis of flood-rich flood-poor periods; and other aspects of major significance e.g. seasonality, magnitude, flood types, analysis of greatest floods, any historical approach etc. - which one would expect to be present and discussed in a paper with this ambitious title - are completely missing. Nevertheless, I think this problem can be easily solved by the authors if they change this part of the title, and instead of "flood history" they write "flood-rich and flood-poor periods".

> Answer:
> Due to current definition of reference books “History” title and content is no objection but to meet the requirements title has been changed into: Flood **sensitivity** of the Bavarian Alpine Foreland…

2) Introduction, first paragraph (p. 7411, lines 4-16): I was just wondering whether the authors left out those Central European studies that are based on long-term discharge reconstructions (e.g. Herget et al. 2010, Wetter et al. 2011), or recent Danube-related investigations (e.g. Rohr 2013, Kiss-Laszlovszky 2013) since they think it is not necessary to list them all here in the introduction, or it was only accidental.

> Answer:
> Well the list is not exhaustive but to meet the requirements most of the suggested supplements have been implemented. Herget & Meurs (2010) have not been listed because ‘discharge reconstruction’ was not the aim of the current paper.

3) Introduction, third paragraph (p. 7412, lines 4-16): It is not very common to use in English "descriptive period" for the documentary evidence coming from the pre-instrumental period.

> Changes:
> “Descriptive period” has been replaced with “period of documentary evidences”.

And then the sentence continues: "and has been obtained from historical writings such as chronicles and compilations." Please rephrase this sentence, because it is very problematic: here one has the impression that the authors are mixing compilations (that is a collection of data taken/excerpted from historical sources, i.e. it is not a source type) with chronicle (which is an important source type from the group of narrative evidence).

Answer:

- But that's exactly what we have done: to expand the data basis we have applied a methodical practice named "non critical approach" (NCA). Data has been analyzed to the gist 'Flood'. The gist 'flood' is the common intersection of compilations and chronicles. NCA is now more elaborate described, see below:

To expand the data basis as wide as possible we have applied a methodical practice we have named "Non Critical Approach" (NCA) (cf. Böhm 2011). The NCA is a procedure especially designed for extraordinary hydrological events. Within the range of historical climatic data, flood information has an exceptional position. Common threads connecting available flood information are damages which have led to burdens on former neighbors. The main argument for the NCA is based on the reasonable assumption that historical flood reports - due to the particular burdens - contain more objective information than other descriptions of climatic events. In the center of this approach stands the tradition of the gist of 'flood event' trough time. Starting point of this approach was the fundamental question if anonymous sources in general may be regarded as verified sources (cf. e.g. Augsburger Anonyme Chronik von 1368 bis 1406. In: Die Chroniken der schwäbischen Städte. Augsburg, Band 1. Leipzig 1865). According to a rigorous interpretation of source criticism all of the (environmental-related) information of this source would have to be discarded. Based on the NCA we use all available sources and information about flood events of the outer-alpine river sections concerning the period of documentary evidences. Avoiding classical source criticism the NCA contributes to increase acquisition of information and reduces the thinning of relevant information during times of limited flood documentation. This approach minimizes the loss of original written records concerning historical flood information due to anthropogenic or natural calamities.
To verify the NCA various stress tests have been trialed. Glaser et al. (2002) state that a spatial criterion for the distribution pattern of weather-climatic causes can be implied by sufficient data density. Within the scope of the NCA a spatiotemporal/synoptical criterion has been consulted to verify historical data. All superior flood events of the Bavarian Foreland have been visualized by spatiotemporal flood distribution pattern with the assistance of geographic information systems. Therefore plausible (spatiotemporal/synoptical) evidence for the validity of flood information can be adduced. Further confirmation was given by cross-comparison with verified records, e.g. HISKLID (cf. Böhm 2011).

Environmental psychological aspects provide a further backing for the NCA. In brief damaging flood events have an exceptional position in cultural history and the transfer of information through time based on primal fear still contains the gist. A more de-tailed description of the NCA is to be found in Böhm (2011).

Mixing together these two terms suggest in this form as if the authors were not aware of the fundamental difference between these two materials (i.e. also the quality difference of these two materials in their own database), which is - I am sure - not the case.

Answer:
For sure, authors are aware of the differences. To justify the merging of the different data basis above mentioned NCA was created.

This problem otherwise also appears in Chapter 3 (Database). Out of the 6 rivers studied, four are direct tributaries of the Danube, while the remaining two (Wertach and Salzach) are tributaries of two of the mentioned tributaries (Lech, Inn).Thus it would be important to know: How did you merge (what method did you use)
C5420
the 6 flood series?

Answer:
The aim was a superordinate spatial unite based on recent administrative borders under consideration of floods as function of atmospheric parameters. The merging of the single time series should reveal the flood-sensitivity of the superordinate spatial unite Bavarian Foreland. All floods of the period of documentary evidences, including intensity levels 1, 2 and 3 were considered.

Changes:

- Paper has been supplemented about all single time series, compare “new” fig. 3.

- Chapter ‘Methods’ has been supplement with following paragraphs:
  For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

- To reveal the flood sensitivity of the entire Bavarian Foreland, all flood events of the outer alpine region have been merged into one overall time series. The highest classification according to damage reports has been counted whereas local events caused by i.e. flash-floods have not been counted. Hence only mesoscale hydrological events have been incorporated into the present analysis.

It would be great if you provide here a basic overview figure concerning the number of flood events related to each studied rivers (in one graph, maybe rivers indicated with different colours). This would give basic information to the reader about the overall weight of the individual rivers in your reconstruction (and it becomes especially important concerning the early period when less data are available).

Like mentioned above:

- Paper has been supplemented about all single time series, compare “new” fig. 3.

Additional modification:

- A synoptical table concerning the data, separated by the different catchment areas has been supplemented:

Table 3. Synoptical tabel of data basis 'flood frequencies Bavarian Foreland'. Columns a-c contain all outer alpine flood events of documentary evidences until 1880. Columns d-e contain all floods derived from instrumental periods until 2008 for one representative gauge per river

River	a) Level 1	b) Level 2	c) Level 3	d) EIP/MIP level 2	e) EIP/MIP level 3
Iller	32	53	15	45	13
Wertach	37	79	20	66	16
Lech	101	159	80	78	38
Isar	88	101	29	55	18
Salzach	154	113	78	56	22
Inn	79	82	63	48	7

It is also important to know how you treat and calculate in the overall series when all your
studied rivers were in flood in the same time (i.e. 1 event or 6 events etc.).

Like mentioned above:

- For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

4) Chapter 2: I have overall good opinion about this chapter: it is short, concise, and still all the important aspects are included.

5) Chapter 3 Database: first paragraph on the applied source materials (p. 7414, lines 10-26) Based on the short description and the rather strange use of historical terminology, one’s first impression is that the authors are not really familiar where their data
exactly come from. Although I am sure this is not the case.

Answer:

- Chapter ‘Database’ has been supplement with a more detailed description of the used data and organization of the database IBT. A comparisons with related papers (cf. e.g. Schmocker-Fackel & Naef 2010, Jacobeit et al. 1999) exhibits that the description of the used data corresponds approximately with mine: brief and succinctly.

- Of course I can prove the data source of each individual flood. But the intention of the current paper was not the discussion of a dataset but the data analysis. Each individual flood has been taken out of a multitude of different sources. A release for the data of Bavarian Foreland under ‘tambora.org’ should be soon realized.

It is fine that there wasa funded research project, and the cooperation with the largest German historical cli-matology databank, the HISKLID, is impressive.

However, the authors have a couple of ’dreadful’ sentences here, and without a complete rewriting of these sentences this paper should not be published. E.g. "The evaluated written evidences originated from handwritings and chronicles (e.g. .... the comments to this comes later....), annuals, historical print media, compilations."

Answer: Revised paper was proof-read by professional.

What do you mean under "handwritings"?

Answer:
Handwriting was used as synonym for manuscript but terminology has been substituted with “manuscript”.

Do you mean the term "manuscript"? If you mean all hand-written documentation, then you should specify it more according to types (i.e. narrative sources such as chron-icles, annals, diaries; or e.g. letter, charters; or leg-administrative sources such as accounts etc.). Because "hand-written" in itself gives us basically no information about the sources applied (or its strength or weaknesses). Moreover, naturally, all chronicles (and any other written materials) until the 1470s are hand-written, and even in the next centuries most of the chronicles and many other sources are hand-written (often later printed). In brackets you mentioned as an example for the origin of "evaluated written evidence" the publication series of the Historical Commission of the Bavarian Academy
C5421
of Sciences, in 37 volumes. I presume you mean the "Die Chroniken der deutschen Städte" series, including narrative source evidence (contemporary, non-contemporary mixed) referring to the 14th-16th centuries. If this is the case, maybe it would be useful to refer to the series title itself here, and also add it to your bibliography (and from thisseries only some of the volumes actually refer to Bavaria).

Answer:
Well, indeed „Die Chroniken der deutschen Städte“ are meant and all of them have been published by Historical Commission of the Bavarian Academy. In

that context I can’t see a wrong citation, please compare ‘references’. Referring to the IBT and its isochronal approach to floods within a Central European context not only the chronicles of Bavaria have been taken in account.

And it would be useful to refer to 1-2 other major source edition series (e.g. with more critical source evaluation such as the MGH) you most probably also applied in your analysis (in the same way as you also referred to a number of compilations later).

- To meet the requirements the continuous text has been supplemented, see below:

  To highlight some selected sources the ‘Chroniken deutscher Städte’ (Chronicles of German Cities 1862 –1968) focused to the city of Augsburg upon river Lech and the publications of Stahleder (1995 – 2005) for the city of Munich upon river Isar will be introduced briefly. Within the ‘Chroniken deutscher Städte’ the chronicles about the city of Augsburg must be highlighted especially. Inside the superior ‘Chroniken deutscher Städte’ the history of Augsburg is organized into ‘Die Chroniken der schwäbischen Städte’ (The chronicles of Swabian Cities, Augsburg 1865 – 1929). For the second oldest city of Germany in total seven volumes are existent including substantial information about river Lech floods. Within these seven volumes the following chronicles have been edited: Volume 1 (1865) contains the ‘Augsburger Anonyme Chronik’ from 1368 – 1406 with proceeding until 1447, the chronicle by Erhard Wahraus from 1126 – 1445 with supplements until 1462 and the chronicle from foundation of the city of Augsburg until 1469. Volume 2 (1866) contains the chronicle by Burkard Zink from 1368 – 1468. Volume 3 (1892) contains the chronicle by Hector Mülich 1348 – 1487 and the anonymous chronicle from 991 – 1483. Volume 4 (1894) includes the chronicle from oldest time of the city until 1536 plus proceeding of the chronicle by Hector Mülich. Volume 5 (1896) contains 'Cronica newer geschichten' by Wilhelm Rem 1512 – 1527, Johannes Franks ‚Augsburger Annalen‘ from 1430 until 1462 and supplements concerning the chronicle by Clemens Sender. Volume 6 (1906) contains the chronicle of Georg Preu from 1512 until 1537. Volume 7 (1917) contains two chronicles by apparitor Paul Hektor Mair. Volume 8 contains ‘The Diary of Paul Hektor Mair’ from 1560 – 1563 and the second chronicle by Paul Hektor Mair 1547 – 1565. And volume 9 contains the weaver chronicle by Clemens Jäger from 955 – 1545.
  Helmuth Stahleder, ex-alternate director of the ‘Stadtarchiv München’ (city archive Munich) evaluated all data within the city archive of Munich to compensate the miss-ing of history of Munich within ‘Chroniken deutscher Städte’. Foundations of this compilation among others are original documents, calculations of city treasurer and yearbooks. Result of the longstanding investigation was the ‘Chronik der Stadt Mün-chen’ in three volumes concerning the history of Munich between the years 1157 – 1818. A multitude of flood events along river Isar are recorded within ‘Chronik der Stadt München’. Each record is furnished with a related city archive reference.

What do you mean under "annuals"?

Answer:

Annuals is/was used as a synonym for yearbooks or annals and has been substituted with the suggested word.

Probably it is a mistyping instead of the term "annals", a large source group of narrative evidence.

What do you mean under "print media"? This is general and unspecified: please, provide the main source types (or groups) you used. E.g. do you mean newspapers, pamphlets, journals or also printed scientific works, narratives etc.?

Answer:
Print media means the historic newspaper of the investigated area, the terminology now is more extensive described and examples for newspaper have been supplemented: …historical dailies of the investigated area (cf.e.g. Augsburger Postzeitung 1833-1935, Innsbrucker Nachrichten 1854-1945).

Please, also check whether the "united leaflet database (...; Ferdinandeum Innsbruck Administration of Inheritance)" is the correct English term of the database and the institute you mention.

Answer:
Please compare p. 7414: The mentioned database is un-edited not united. Unedited as synonym for unpublished.

- http://www.tiroler-landesmuseen.at/page.cfm?vpath=haeuser/ferdinandeum/haus&switchlocale=**en_US**

And finally, again the basic problem of listing (and mixing) primary sources together with compilation. Please make a clear distinction here as it is a totally different thing: so, please, mention the applied compilations in clear separation from original, primary sources. I also recommend to have a language check here. In general, I suggest to rewrite the first long paragraph, and I recommend to be more careful and provide a more elaborated, clear description about the fundamentals of your database, with an appropriate use of basic historical source terminology.

Please compare answer and supplements under point 3) of your specific comments.

5) Chapter 3 Database: Concerning the rest of the chapter, the homogenisation of instrumental series as well as merging between overlapping periods are well-elaborated, and the brief description of the 3-scaled index classification is clear and appropriate.

I only have one little comment here: maybe there is a simple mistyping in line 17 (p. 7415): here most probably you meant "flood descriptions" instead of "weather descriptions".

Answer:
Indeed “weather descriptions” is meant, now supplemented with “descriptions of weather conditions”.

I also find it very positive that the authors in their datasets have an appropriate overlap (1826-1880) between the pre-instrumental/documentary period and the instrumental period.

I have some comments to the method described in the last paragraph of
C5422
the Chapter (p. 7416): I understand that some researchers use datasets regarding the pre-instrumental period "with and without source-critical evaluation", i.e. no evaluation
of individual sources and historical quality-homogenisation (only statistical) have been
carried out. It is also true that in this way much less data is filtered out (compared to proper historical critical evaluation), and as a result potentially a larger dataset can be gained. However, this approach has some significant dangers which can significantly alter the analysis results at the end. So, I appreciate the fact that the authors mention that they use the "non critical approach", but with this comment the problem is still not
solved. I also agree with the authors that some of the pitfalls can be avoided with "a methodological practice verified inter alia by cross-comparison with verified records". In the (later) periods when great amount of (detailed) evidence is usually available concerning each single flood events (e.g. for medium- and large-scale events) this approach might work. Nevertheless, the early periods with less and less contemporary source evidence and more non-contemporary sources (with copying each-others dating mistakes, and in this way potentially doubling, trippleing flood events; and this is especially true for the Middle Ages), cross-comparison in itself does not really provide much help in identifying wrong dating etc.

> Answer:
> Well it's a fundamental question take the risk of doubling/tripling flood events or take the risk to miss flood events because of missing primary sources. Due to the approach of understanding floods as a function of climatic circumstances the main-author decided to take the last-named risk provided by the "Non critical approach".

And this has the consequence that uncertainties greatly increase in the early part of the series, and therefore the validity of the analysis results concerning the early period can be basically questioned. As we could see earlier, the authors did not make a clear differentiation between primary sources and compilations (collections taking data from primary sources). This makes a bit also unclear what they cross-checked with what, i.e. what they mean under "verified
records"?

> Answer:
> All data from HISKLID and CLIMDAT are regarded as verified records. Additional within the scope of the NCA we have exerted a spatiotemporal/synoptical criterion has been consulted to verify historical data. All superior flood events of the Bavarian Foreland have been visualized by spatiotem-

poral flood distribution pattern with the assistance of geographic information systems.

For example, if a compilation data is cross-checked with a chronicle data, then it can easily happen that we compare the same information (i.e. the compilation uses the same chronicle, and then we check the same thing with itself - I do not mean that is what the authors actually did, but probably such questions about the methodology could be briefly clarified).

Please cf. 'Method' chapter: superordinate floods have only be counted once (cf. 1501 summer Flood). And due to the chosen method of 31year sliding means potential misdating will be relativized. From a historical pint of view unsatisfying from a meteorological/climatological point of view justifiable because the focal point of the present investigation is the flood sensitivity/susceptibility of a superordinate region due to climatic parameters and not the analysis of one real flood event.

Answer:
Samples which have been checked followed the source content through time, from "youngest" chronicles until the oldest evidences. Under cross-checking we also understand meteorological perimeter for one event, so cross-checking has been applied under consideration of recent distribution of precipitation and weather conditions.

I think these raised uncertainties/questions can be partly solved after clarifying the first part of their database chapter, and when the authors provide some more information (i.e. a couple of more sentences) on how they did the
C5423
verification in practice.

6) Chapter 4: Methods I have some comments to the end of the chapter: a) Lines 15-20 (p. 7417): The authors specifically refer to the 1501 flood mark in Passau located at the Fischmarkt. Recently, this flood mark was moved significantly higher from its earlier place. Do you use the old maximum water level mark or the new one in your analysis?

Answer:
Due to the classification into three intensity levels, both of the mentioned marks reveal a class 3 event. That's because classification underlies damage reports and not discharge reconstructions.

b) Last sentence: "Different databases and data densities (e.g. 14th/15th century - the period of the Renaissance - beginning of the instrumental period) were thus considered as well as possible." It is not very fortunate to mix dates with cultural periods because from the sentence it is not clear what time span you mean. 14th-15th century is clear, but the Renaissance as a cultural period was already present in the 15th century in Europe (even if not in all parts, of course), and there are other cultural periods in Europe before the beginning of the instrumental period (thus, you have not defined the beginning and end of the referred period). It would be just easier and more clear to give simply centuries/dates.

Answer:
Renaissance has been substituted with “turn of the 15th to 16th century”.

7) Chapter 5: Results Could you please describe the method ("Polynomial function of the 5th degree") you applied in the identification of flood-rich flood-poor periods? The
application of this method has great importance in your overall analysis and fundamentally affects the results. It would be also important to know why the authors chose this particular method (and why not others, why the authors think it is better for their purposes than others), and what are the basic advantages and disadvantages of the applied methodology?

Answer:
This method considers the different data density through time in a proper way, from poor data density at the beginning of the time series onto the transition of written evidences into the instrumental period. The chosen method is subjective but experiences its quantitative justification by t-test analyses in a statistical way.

Changes to the issue ‘polynomial’ in chapter ‘Methods
This method does not claim precision for the beginning and the end of the defined periods but compared to a multitude of other methods and due to the changing data density over time it is the highest-performance method. Different methodical approaches with the aid of quantiles as medians or percentiles could not achieve satisfactory definitions for the generated time series and its comparability. The determined periods should come over as the results of a sensitivity analysis.

The authors properly refer back to the paper written by Glaser
and Stangl (2003b), but - checking back that particular paper - the method itself and why that method was chosen are not described there either.

Answer:
The citation of Glaser & Stangl 2003b refers to the t-test and not to the polynomial function. But application of polynomial function to visualize long-term development can be found by Glaser et al. (2004).

And, just by a simple look at your Figs. 3 and 4 (but esp. Fig. 4), it is not obvious at all whether the break points you identified by using the applied method really identify in each case the beginning and the end of a flood rich period (or they identify something else).

Answer: Like mentioned above: This method does not claim precision for the beginning and the end of the defined periods but compared to a multitude of other methods and due to the changing data density over time it is the highest-performance method.

Lines 16-17 (still on p. 7418): "A rising data density after the mid-15th-century must be seen in a context of the intervention of letterpress." It is not a "must be seen" question. There are also
C5424
other important historical-cultural reasons for this change. So, if you want to keep this sentence, then at least please add: "amongst other important reasons" (or something alike).

Modification: “amongst other social reasons” has been added.

8) Sub-chapter 5.1: Flood-rich period #1: 1300-1335 Due to very low density of data, I think this period should be discussed in more detail. It would be useful to include briefly: How, based on what flood evidence?? in your series, did you define the beginning (and the end) of this period?

Answer:
In general weak data density before the 16th century now is highlighted several times, cf. e.g. Fig. 4.

Supplements:
Within the investigation area 16 records could be raised from compilations like Alexandre (1987) and different chronicles (cf. e.g. Zillner 1885, Schnurrer 1823) and the Augsburger Urkundenbuch Nr. 264 (cf. Gross 1967). Despite small data density significant changes of climatic parameters can be stated and should not be withheld.
…
A further qualitative confirmation for particular climatic circumstances during that period is provided by Lamb (1982).

Concerning this flood rich period there is very low number of data available (Fig. 3), and this problem was (I presume on the earlier general information) solved with using interpolation (see also Fig. 4). I have a number of problems here:
a) In the early part of the 14th century contemporary sources referring to floods in Bavaria are only exceptionally available (please, correct me if I am wrong): most flood information known (e.g. especially those included in the historical editions series you mentioned "Die Chroniken der deutschen Städte") comes from later chronicles with dating errors etc.

Please compare supplements above. But ‘Chroniken deutscher Städte’ play a minor part within early 14th century.

If I see it well in Fig. 3, your few data concerning this period is accumulating around the mid-1310s, i.e. the years 1315 and/or 1316 (+-1-2 years), which are also known as the famous flood years on the Danube, and then 1-2 after this period (maybe one in the 1320s? and 1-1 in the 1340s? or around 1350?). So, in the original database, represented in Fig. 3, you basically have a few flood data around the mid-1310s, and then only 1-1 individual events scattered.

Just by simplethinking: how can from this data a defined flood rich period of 1300-1335 come out?

> Flood information are existing for the years 1310, 1314, 1315, 1316, 1317, 1321, 1322 und 1329. That means within 20 years 9 flood events can be attested and I think that accumulation can be denoted period. Beginning (1300) and ending (1335) of the period are induced to 31-year sliding mean.

And then we have not yet even considered such questions that, due to very low density of sources, you might have data doubling or trippleing due to simple misdating of non-contemporary authors, because here there is not too much contemporary to check with (or maybe there is, but then it would be really important to specify, because that would support the validity of you work concerning this early part).

And since the analysed series is defined based on 6 flood series, then it can also happen that one single flood (which affected all rivers in Bavaria) and/or its misdatings make up for you this relative flood-rich period. Simply saying: unless the authors prove the validity of this flood-rich period based on their data and the sources, due to the very low number of data
C5425
and the high uncertainty quality-level of their data (also due to the applied verification methodology) concerning the early 14th century, the authors can maximum suggest this flood period as a hypothesis, but not as a period based on realities (i.e. you either give more proofs why it is really a flood rich period, esp. concerning the 1320s and early 1330s, or I would recommend to leave it out or mention it only as a hypothesis).

> Due to the chosen method of 31year sliding means potential misdating will be relativized. From a historical pint of view unsatisfying from a meteorological/climatological point of view justifiable because the focal point of the present investigation is the flood sensitivity/susceptibility of a superordinate region due to climatic parameters and not the analysis of one real flood event.
>
> Answer:
> The first sentence of chapter 5.1 refers to the "low data density". So the "weakness" of this first period is already highlighted.

It is another question that in the broader neighbourhood of the study area this period is - with the clear exception of the decade of the 1300s and 1310s - not really among the particularly humid periods (e.g. see the related literature referred in the Introduction).

> Answer:
> Please compare Wanner et al. 2000, Lamb 1982

To a lesser extent, this is still also valid for the next medieval flood period. But - in general - from the later parts of the 14th, and especially in the 15th century more contemporary sources are available also in Bavaria, and this makes analysis more possible (i.e. no critics here).

9) Chapter 5.3 (p. 7420), last sentences (but also implies on 5.10.2): Which correlation

do you use while comparing your series to the NAO indices (and why)?

Answer:
Pearson-coefficients have been calculated. The correlation should reveal potential coherences between the frequency of occurrence of floods and the atmospheric parameter NAO.

10) A short question to Fig 3: What does the grey line (with the question mark) mean there?

Answer:
Sorry, can’t find a grey line except the columns for floods per annum. Do you mean the red polynomial? The question mark refers to the fact of doubtful and missing data before the 14^{th} century. But former Fig. 3 has been redrawn concerning different aspects, please cf. Fig. 4.

11) The "6 Discussion" chapter looks rather like a "Conclusions" chapter: maybe it would be useful to rename it accordingly. However, I do agree that a Discussion chapter (with different content) would also have relevance here. For example, the authors have not discussed some important and potentially interesting questions; e.g. they have not compared their results to any other results available in Europe or at least in the neighbouring areas.

Answer:
Chapter 6 has been renamed in ‘Conclusions’. A confrontation with other time series has been added in Chapter 5 ‘Results’.

Changes (added in Chapter 5):
The flood frequencies of the Bavarian Foreland in confrontation with selected flood frequencies of Central Europe
This confrontation is limited to the period between 1500 and 1900. The limitation is founded due to weak data density in general before 1500 and due to a multitude of anthropogenic overprints of the river systems around the beginning of the 20^{th} century. The comparison will be limited to the Lower Rhine and Middle Rhine (cf. Glaser 2008) and Vlatva (an Elbe tributary) and the Czech Elbe itself (cf. Brazdil 1998). The confrontation is depicted in table 4. Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Similarities for all time series can be particularly highlighted for the second half of the 16^{th} century. In general an unexpected similarity can be stranded between the time series Bavarian Foreland and the Lower Rhine, except the years 1790 until 1819. Good accordance between the Bavarian Foreland can be revealed for the first and seventh and eighth decade of the 16^{th} century. During the 17^{th} century only the sixth decade shows good accordance. Again good accordance can be highlighted for the end of the 18^{th} and beginning of the 19^{th} century. Reasons for this variable behavior are founded in the variability of general synopsis and resulting weather conditions. In that context the above mentioned NAO is playing a vital role. For a further understanding of the variability between the confronted time series meteorological aspects must be consulted.

Table 4. Confrontation of selected flood frequencies. Lower Rhine (RHl), Middle Rhine (RHm), Czech Elbe (ELBcz), Vlatava (VLA) and Bavarian Foreland (BF). Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Data altered according to Glaser (2008) and Brazdil (1998).

	RHl	RHm	BF	ELBcz	VLA	
1500						1500
1510						1510
1520						1520
1530						1530
1540						1540
1550						1550
1560						1560
1570						1570
1580						1580
1590						1590
1600						1600
1610						1610
1620						1620
1630						1630
1640						1640
1650						1650
1660						1660
1670						1670
1680						1680
1690						1690
1700						1700
1710						1710
1720						1720
1730						1730
1740						1740
1750						1750
1760						1760
1770						1770
1780						1780
1790						1790
1800						1800
1810						1810
1820						1820
1830						1830
1840						1840
1850						1850
1860						1860
1870						1870
1880						1880

1890						**1890**
1900						**1900**

This, rather reasonable, comparison part is completely missing
from the paper, and should be included. The authors compared their results to e.g. sunspot numbers, but - compared to this - other elements, for example, a systematic comparison with volcanic eruptions would be also probably worth for a paragraph in the Discussion (this is only a suggestion; sometimes the authors mention period "triggered by multiple volcanic eruption". However, some of the greatest eruptions happened in their flood poor periods etc.). It is also interesting, for example, that the 1780s -
C5426
particularly flood-rich on large sections of the Danube - is part of a flood poor period in the Bavarian Forelands flood reconstruction.

Answer:
The reviewer raises an interesting aspect, until now unfortunately not trailed in detail.

Based on the above-mentioned reasons, as reported at the beginning, I suggest major revision. However, I would like to stress that I find this paper as an important contribution, and - after some necessary changes - clearly worth for publishing in the related special issue of the HESS journal

Flood sensitivity of the Bavarian Alpine Foreland since the late Middle Ages in the context of internal and external climate forcing factors

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Abstract

This paper describes the flood sensitivity of the Bavarian part of the Alpine Foreland of Germany and addresses different questions concerning climate variability and flood frequencies, from the 13th century until today. Focal point of the paper is the flood frequencies of the superordinate spatial unit of the Bavarian Foreland but not the ones of its single time series. Will recent climatic change modify the flood frequencies within the Bavarian Alpine Foreland or have the flood frequencies been varying due to altering climatic conditions since historical times? In the context of recent discussions whether man-made climate change will modify the present state of flood frequencies, a look back into the past is essential to understand the occurrence of floods in general and of recent floods in particular. In order to understand climatic variability and changes in a comprehensive way, it is necessary to review long time series. A perceived increase of summer floods in eastern Germany and Bavaria since 1997 requires examination of long time series to estimate changes in flood frequencies in a proper way. In view of the annual distribution of flood events within the Alpine Foreland of Germany, summer floods prove to be most important. Based on written historical sources, the flood history of the Alpine Foreland of Germany can be reconstructed back to the 14th century. One major result is the occurrence of 'flood-rich' and 'flood-poor' episodes in almost cyclical sequences. Flood-rich periods, before the 16th century based on weak amount of available date, were recorded in the periods 1300 – 1335, 1370 – 1450, 1470 – 1525, 1555 – 1590, 1615 – 1665, 1730 – 1780, 1820 – 1870, 1910 – 1955 as well as in a ninth period beginning in 1980. The flood-rich periods are characterized by longer flood duration. Most of the flood-rich and flood–poor periods (in particular the beginning and the end of them) can be connected to changes in natural climate variability. These include changing sunspot numbers (as a measure of solar activity), so-called **L**ittle **I**ce **A**ge **T**ype **E**vents (LIATEs) as well as changes in the North Atlantic Oscillation (NAO).Climate signals from external forcing factors, which could be used to explain the changing flood frequencies in the Bavarian Alpine Foreland, end in 1930. Relationships within the climate system such as the correlation of flood frequencies with the NAO have changed during the transition from the post Little Ice Age period to the Modern Climate Optimum around 1930. Natural climate variability might have been outperformed by anthropogenic climate change.

Key words Bavarian Alpine Foreland, flood history, flood frequencies, climate signals, forcing factors

1 Introduction

Historical climatology, especially the branch addressing historical floods, has gained increasing interest during the last decades. Different parts of Central Europe have been investigated. Schmoecker-Fackel & Naef (2010), Pfister (1984, 1996, 1999) and Wetter et al. (2010) have for instance analyzed the flood history of Switzerland, Brázdil et al. (2005) have examined the flood history of the Czech Republic, Böhm & Wetzel (2006), Mudelsee et al. (2004), Deutsch & Pörtge (2001, 2002), Deutsch et al. (2004) and Glaser (2008) have investigated different parts or catchment areas of Germany, while Rohr (2008, 2013) has examined extreme natural events in Austria, floods included. Sturm et al. (2001) and Glaser & Stangl (2003a, b) have analyzed different European flood histories with a focus on Central Europe. Kiss & Laszlovszky (2013) have examined partial areas of the Danube for the western and central Carpathian Basin.
Nevertheless, the flood history of the entire Bavarian Alpine Foreland has not been systematically analyzed until now (cf. Böhm 2011). Additionally, the Bavarian Alpine Foreland represents a region with a high susceptibility to climatic changes (cf. Auer et al. 2007). The Bavarian part of the Alpine Foreland of Germany (hereafter termed Bavarian Foreland) has experienced flood events on a regular basis, but the return periods, e. g. for strong floods as well as for flood-rich or flood-poor periods, cannot be derived from standard reference periods of 30 years. All of the recent major summer floods have been triggered by cyclones following a special pathway (cf. van Bebber 1891). This so-called Vb cyclone track seems to be the main precondition causing catastrophic flood events in the Bavarian Foreland, currently and also in the past (yet not every Vb cyclone affects the investigation area in total). Reconstructions of historic weather patterns show the emersion of this phenomenon in the past (cf. Böhm 2011). The recent period, starting 1997, has experienced numerous floods triggered by Vb-conditions during the summer months. The so-called "(River) Oder Flood 1997" and the "Pfingsthochwasser (Whitsun Flood) 1999", both of which took place at the end of May, can be compared to the following summer floods of 2002 (Elbe/Danube Flood) and 2005 (Alps Flood). All these floods (despite their special naming) have affected the Bavarian Foreland.

To generate a long time series, it was necessary to integrate three different periods of flood documentation. The oldest pieces of information originate from the so-called period of documentary evidences and have been obtained from historical recordings such as chronicles and compilations from the late Middle Ages. These written records can be statistically analyzed, as depicted in Glaser (2008). From the year 1826 onward, data are available from the so-called **e**arly **i**nstrumental **p**eriod (EIP) (cf. Jacobeit et al. 1998). From at least one representative gauge station in the lower sections of every alpine river recorded historic water levels can be evaluated. From the beginning of the 20th century until now, modern instrumental data (water level and discharge measurements) are available. The separately evaluated flood histories of the rivers Iller, Lech with tributary Wertach, Isar, Inn and its tributary Salzach have been merged for one overall time series. The merging of the single time series should reveal the flood-susceptibility of a superordinate spatial unit based on recent administrative borders under consideration of climatic parameters. In the methods' section the merging of the single time series is more elaborately described. Single flood events as well as quantification of flood events do not stand in the limelight of the current paper. The time line of the flood history of the Bavarian Foreland includes 584 individual flood events (see methods' section).

2 Investigation area

In this paper the Bavarian Foreland is defined by the lower sections of the catchment areas of the aforementioned rivers. From west to east the research area is bordered by the river Iller in the west and the rivers Inn and Salzach in the east, as depicted in Fig. 1. The headwaters, however, are located in the Alps so that all of the rivers are northern-alpine mountain rivers (apart from the river Wertach which should be regarded as a foreland river). The main rivers Iller, Lech, Isar and Inn are Alpine tributaries of the Danube river.

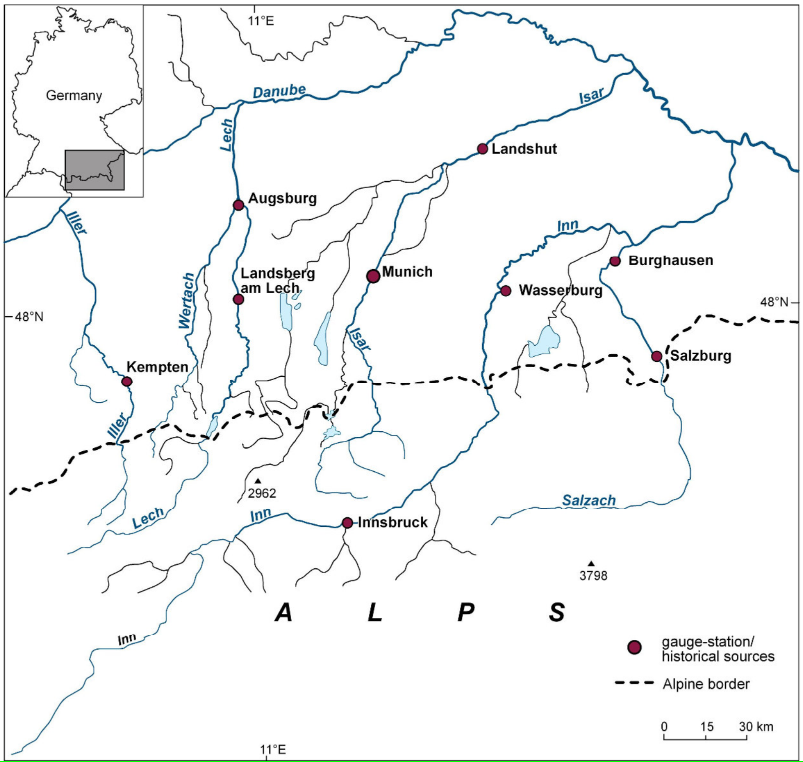


Figure 1. Investigation area "Bavarian Foreland" is bordered by the rivers Iller, Danube, Inn/Salzach and the Alpine border (dashed line). Red spots are locating outstanding historical locations and gauges.

All the rivers coming from the Northern Limestone Alps traverse the Flysch Zone, enter the area of the faulted Molasse sediments and cross the belt of Pleistocene moraines and gravel fields. The substratum of the lower sections of the rivers is formed by sandy sediments of the Molasse trough. All traversed geological formations differ in their east-to-west extension. The geological formations of the outer-alpine stream segments are of particular interest because of their texture. Due to the texture of the subsoil and anthropogenic encroachments from 1850 on, the riverbeds have become deeper. About 1850 Bavarian Administration systematically started riverbed corrections in order to prevent floods, to protect infrastructure like railways and roads and to support agriculture to the fertile plains and meadows supplying the growing population. In Fig. 2a one can see the beginning of the anthropogenic encroachments due to the results of gauge measurements, starting around 1860. The Gauges' neutral points have not been changed, staff gauges have been prolonged into the negative measurement range. These circumstances affect hydrological interpretations concerning the EIP. To assure homogeneity in the comparison of flood events of individual time series, a high-pass-filter has been applied (see methods). The regional distribution of annual precipitation differs from around 600mm/a in the region of the Danube river to 2500mm/a and more within the highest elevations of the investigation area. The share of alpine catchment is important for the runoff of the headwaters into the Bavarian Foreland due to its function as temporary water storage reservoir and orographic barrier. In Table 1 the reference data of the relevant rivers are listed.

Table 1. Reference data of the Bavarian Foreland rivers, modified after different authors. The information "Medium Discharge Summer" refers to the lowest official downstream gauge

River	Headwaters	Rivers Length	Overground Catchment Area	Medium Discharge Summer
Iller	Allgäu High-alps (Germany)	~ 160 km	2215 km²	79,3 m³/s (Gauge Wiblingen)
Wertach	Allgäu Alps (Germany)	~ 135 km	1290 km²	16,7 m³/s (Gauge Türkheim)
Lech	Rhaetic Alps (Austria)	~ 250 km	4162 km²	136 m³/s (Gauge Augsburg)
Isar	Karwendel Mountains (Austria & Germany)	~ 260 km	8960 km²	191 m³/s (Gauge Plattling)
Inn	Maloja Saddle (Switzerland)	~ 520 km	26100 km²	972 m³/s (Gauge Passau)
Salzach	Kitzbühl Alps (Austria)	~ 220 km	6700 km²	332 m³/s (Gauge Burghausen)

In the Bavarian Foreland we can differentiate spatial and chronological aspects of flood genesis as a function of hypsometric distribution and thereto linked the snow retention into the individual catchments. We can observe a west-east gradient contrasting the chronological annual mean discharge maximum starting in the western part with the investigation area with a spring peak (rivers Iller and Wertach). The catchment areas of the rivers Lech and Isar, located in the central part of the investigation area, are denoted by a distinctly marked summer peak, followed by the eastern part with prolonged summer peaks (rivers Inn and Salzach). This spatial distribution is reflected by the seasonal distribution of the flood events indicated in Table 2.

Table 2. Seasonal distribution of flood events (percentages refer to the individual outer-alpine river sections) in the Bavarian Foreland for the period of 14th century – 2008

	Iller	Wertach	Lech	Isar	Inn	Salzach
Summer	42%	39%	57%	58%	79%	73%
Spring	16%	20%	14%	14%	10%	6%
Winter	28%	23%	12%	12%	2%	7%
Autumn	14%	18%	17%	16%	9%	14%

Due to the spatial distribution of the catchment areas within the Northern Limestone Alps and the Bavarian Foreland, the highest proportion of summer floods occurs in the eastern river sections of Inn (79%) and Salzach (73%), followed by Isar (58%) and Lech (57%). Due to the lower extent of the alpine catchment area, the rivers Iller and Wertach only have about 40% of their floods during summer. In total, a dominance of summer floods can be stated for the annual time series. Hereafter the use of annual information is owed to minimized data quality and information before the 16th century. The flood-rich periods of the whole year (depicted in Fig. 6 by blue graph) and of the summer months (depicted in Fig. 8 by blue graph) correspond substantially to each other.

The investigation period of 1300 – 2008 covers the Little Ice Age (1300 – 1850) and the transition period to the Modern Climate Optimum as it is today. According to Wanner et al. (2000), it is advisable to differentiate the Little Ice Age into so-called Little Ice Age Type Events (LIATEs) addressing three major periods of extended glacier tongues. The periods, starting with LIATE3, are depicted for the years 1300 – 1380, 1570 – 1640 and 1810 – 1850.

3 Database

The body of historical source material corresponds to the wide range of settlements along the northern alpine mountain rivers. All of the above-mentioned rivers host at least one notable historical site (among a multitude of other sites, e.g. Kempten (Iller), Augsburg (Lech/Wertach), Munich (Isar), Wasserburg (Inn), Burghausen (Salzach). Within the framework of a DFG- funded (German Research Foundation) research project a database called IBT (Inundationes Bavariae Thesaurus) (cf. Böhm 2011) was developed in cooperation with HISKLID (Historische Klimadatenbank Deutschland - historical climatic database of Germany - cf. Glaser 2008). The former HISKLID has meanwhile migrated to tambora.org. Tambora is the acronym for the climate and environmental history collaborative research environment.
The IBT itself contains more than 32.000 flood events within (Central-) Europe, all of them with a temporal relationship to the 584 independent flood events identified for the Bavarian Foreland (see below). The first investigation period was the period of documentary evidences from the 14th century to the year 1880. The data set of the period of written evidences includes more than 15.000 flood events. The evaluated written evidences originated from manuscripts and chronicles (e.g. the "Historische Kommission der Bayerischen Akademie der Wissenschaften/Historical Commission of the Bavarian Academy of Sciences" has published 37 volumes of city chronicles between 1862 and 1968), annals, historical dailies of the investigated area (cf.e.g. Augsburger Postzeitung 1833-1935, Innsbrucker Nachrichten 1854-1945), compilations (e.g. Sonklar 1883, Weikinn 1958 – 1963, Alexandré 1987, Fliri 1998, Stahleder 1995 – 2005, Börngen & Tetzlaff 2000 – 2002, Brázdil 2005), un-edited historical leaflet database (Schorn † 1937, Ferdinandeum Innsbruck Administration of Inheritance) and already existing databases (Militzer 1998, Glaser 2008) which were re-examined with a focus on the Bavarian Foreland. Due to the approach explained below every written evidence of the middle reaches and tail waters has been considered.

To highlight some selected sources the 'Chroniken deutscher Städte' (Chronicles of German Cities 1862 –1968) focused to the city of Augsburg upon river Lech and the publications of Stahleder (1995 – 2005) for the city of Munich upon river Isar will be introduced briefly. Within 'Chroniken deutscher Städte' the chronicles of city of Augsburg must be highlighted especially. Inside the superior 'Chroniken deutscher Städte' the history of Augsburg is organized into 'Die Chroniken der schwäbischen Städte' (The chronicles of Swabian Cities). In total nine volumes are existent for the second oldest city of Germany including substantial information about river Lech floods. Within these nine volumes the following chronicles have been edited: Volume 1 (1865) contains the 'Augsburger Anonyme Chronik' from 1368 – 1406 with proceeding until 1447, the chronicle by Erhard Wahraus from 1126 – 1445 with supplements until 1462 and the chronicle from foundation of the city of Augsburg until 1469. Volume 2 (1866) contains the chronicle by Burkard Zink from 1368 – 1468. Volume 3 (1892) contains the chronicle by Hector Mülich 1348 – 1487 and the anonymous chronicle from 991 – 1483. Volume 4 (1894) includes the chronicle from oldest time of the city until 1536 plus proceeding of the chronicle by Hector Mülich. Volume 5 (1896) contains 'Cronica newer geschichten' by Wilhelm Rem 1512 – 1527, Johannes Franks ‚Augsburger Annalen' from 1430 until 1462 and supplements concerning the chronicle by Clemens Sender. Volume 6 (1906) contains the chronicle of Georg Preu from 1512 until 1537. Volume 7 (1917) contains two chronicles by apparitor Paul Hektor Mair. Volume 8 contains 'The Diary of Paul Hektor Mair' from 1560

– 1563 and the second chronicle by Paul Hektor Mair 1547 – 1565. And volume 9 contains the weaver chronicle by Clemens Jäger from 955 – 1545.
Helmuth Stahleder, ex-alternate director of the 'Stadtarchiv München' (city archive Munich) evaluated data within the city archive of Munich to compensate the missing of history of Munich within 'Chroniken deutscher Städte'. Foundations of this compilation among others are original documents, calculations of city treasurer and yearbooks. Result of the longstanding investigation was the 'Chronik der Stadt München' in three volumes concerning the history of Munich between the years 1157 – 1818. A multitude of flood events along river Isar are recorded within 'Chronik der Stadt München'. Each record is furnished with a related city archive reference.

The early instrumental records in the Bavarian Foreland started in 1826. More than 20 historical gauge station records were examined. The data set of EIP/MIP includes about 17.000 flood events of the Bavarian Foreland (MIP = modern instrumental period). The data were analysed with respect to monthly maxima of the water level. Taking physical structures and vertical erosion of gauge stations into account, the gauge datum has been changed in some cases, sometimes even repeatedly. A high-pass filter was applied to homogenize the data. In the present paper we choose one representative gauge station for each river, each with the longest coherent time series since 1826. They include the time series of Kempten (Iller), Landsberg am Lech (Lech), Landshut (Isar), Wasserburg (Inn) and Burghausen (Salzach). The EIP time series of the river Wertach was merged between overlapping periods, verified by a high Pearson correlation coefficient (r=0,86) between the data from the gauge stations Ettringen and Augsburg/Oberhausen. From 1900 onward data were available from the Bavarian Water Authority.
Within the IBT all data sets are organized by the following parameters: identification number, event date as accurate as possible (most records are available in daily and monthly resolution), duration of flood, rainfall etc., location with geographic coordinates, river relationship, reference and coding concerning hydrological and climatological parameters and source text. All data of the Bavarian Foreland have been recorded and coded for tambora.org. The activation of the elaborated data base should soon be realized.

To merge the different data periods, we used the following approach: To compare flood events from written historical sources with flood events measured by water level or discharge during the instrumental period, we used an existing intensity classification of historical floods which was adapted to the instrumental period. According to the scheme of Sturm et al. (2001), the flood events were classified into three intensity levels. The classification is based on damage reports and descriptions of weather conditions if available. If flood events were mentioned in rudimentary descriptions only or there was as little as minor damage, the event was classified as a regional flood (intensity Level 1). If damage of water-related structures (e.g. bridges, weirs and mills) or buildings near the rivers have been reported or if there were indicators for long-lasting flooding of farmland, Level 2 was assigned to the flood. The criteria for catastrophic floods, reported from different river systems, are severe damage or destruction of water-related structures, loss of lives, long-lasting flooding of wide areas and geomorphological changes in the fluvial system; those were classified as Level 3. The selected instrumental data are based on the monthly maxima of water level or discharge. The mean values of these measurements plus one, two or three standard deviations define the thresholds for the classification of the instrumental data (in case of water level data high-pass filtered data were used, see methods). According to the experience in working with historical flood information, all floods of intensity Levels 1,2 and 3 from the period of documentary evidence were considered, whereas Level 1 events from the instrumental period were disregarded. An overlapping period (1826 – 1880) between the descriptive and the instrumental periods suggested this procedure. Samples of rudimentary descriptive flood information have shown that the historical flood information through time traditionally is based on strong events for the most part (cf. Böhm 2011). In Table 3 all flood events used for the merged time series “flood frequencies of the Bavarian Foreland” (cf. figs. 3 and 4) are listed. The data for the time series Bavarian Foreland is derived from 1825 different flood records in total which can be assigned to 584 independent flood events.

Table 3. Synoptic table of data basis 'flood frequencies Bavarian Foreland'. Columns a to c contain all outer-alpine flood events of documentary evidences until 1880, segmented after intensity levels. Columns d to e contain all floods derived from instrumental periods until 2008 for one representative gauge per river. EIP = Early Instrumental Period, MIP = Modern Instrumental Period.

River	a) Level 1	b) Level 2	c) Level 3	d) EIP/MIP level 2	e) EIP/MIP level 3
Iller	32	53	15	45	13
Wertach	37	79	20	66	16
Lech	101	159	80	78	38
Isar	88	101	29	55	18
Salzach	154	113	78	56	22
Inn	79	82	63	48	7

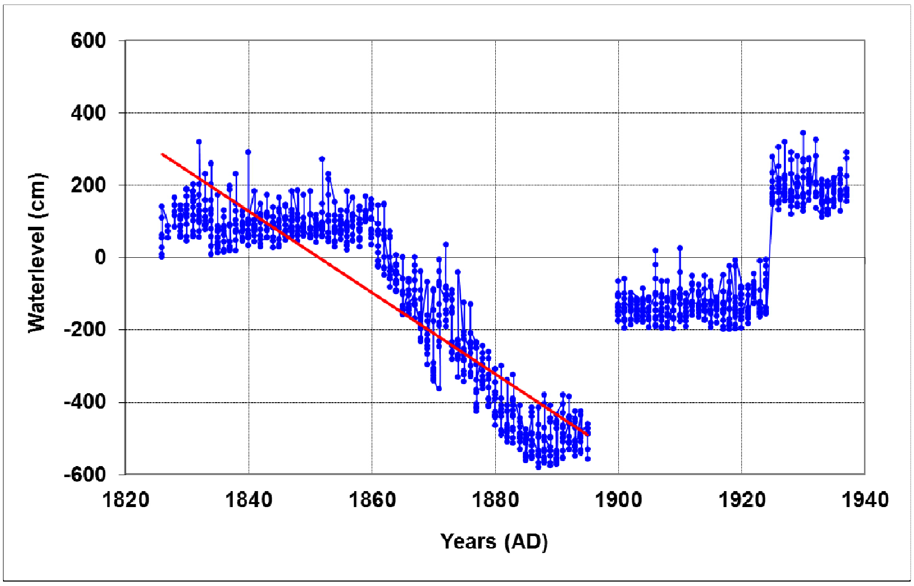
To expand the data basis as wide as possible we have applied a methodical practice we have named “Non Critical Approach” (NCA) (cf. Böhm 2011). The NCA is a procedure especially designed for extraordinary hydrological events. Within the range of historical climatic data, flood information has an exceptional position. Common threads connecting available flood information are damages which have led to burdens on former neighbors. The main argument for the NCA is based on the reasonable assumption that historical flood reports - due to the particular burdens - contain more objective information than other descriptions of climatic events. In the center of this approach stands the tradition of the gist of ‘flood event’ trough time. Starting point of this approach was the fundamental question if anonymous sources in general may be regarded as verified sources (cf. e.g. Augsburger Anonyme Chronik von 1368 bis 1406. In: Die Chroniken der schwäbischen Städte. Augsburg, Band 1. Leipzig 1865). According to a rigorous interpretation of source criticism all of the (environmental-related) information of this source would have to be discarded. Based on the NCA we use all available sources and information about flood events of the outer-alpine river sections concerning the period of documentary evidences. Avoiding classical source criticism the NCA contributes to increase acquisition of information and reduces the thinning of relevant information during times of limited flood documentation. This approach minimizes the loss of original written records concerning historical flood information due to anthropogenic or natural calamities.

To verify the NCA various stress tests have been trialed. Glaser et al. (2002) state that a spatial criterion for the distribution pattern of weather-climatic causes can be implied by sufficient data density. Within the scope of the NCA a spatiotemporal/synoptical criterion has been consulted to verify historical data. All superior flood events of the Bavarian Foreland have been visualized by spatiotemporal flood distribution pattern with the assistance of geographic information systems. Therefore plausible (spatiotemporal/synoptical) evidence for the validity of flood information can be adduced. Further confirmation was given by cross-comparison with verified records, e.g. HISKLID (cf. Böhm 2011).

Environmental psychological aspects provide a further backing for the NCA. In brief damaging flood events have an exceptional position in cultural history and the transfer of information through time based on primal fear still contains the gist. A more detailed description of the NCA is to be found in Böhm (2011).

4 Methods

In Fig. 2 the monthly maxima of water levels, exemplified by the gauge Ettringen/Wertach (35km south of Augsburg) before (a) and after (b) high-pass filtering are depicted. Fig. 2a shows the deepening of the riverbed due to anthropogenic encroachment into the river system. The process of riverbed deepening started around 1860. Since the administration didn't change the datum of the measuring device for a time, but extended the measuring sticks of the gauges into the negative range instead, a total riverbed incision of more than 6 m within 30 years is documented. Furthermore, first counter-measures (like lateral water-buildings) obviously occurred around 1870. Around 1885 the incision seems to have stopped. After a short data gap around 1895, two datum changes can be identified. The high-pass filtering seems to be the most suitable method to address these different changes.



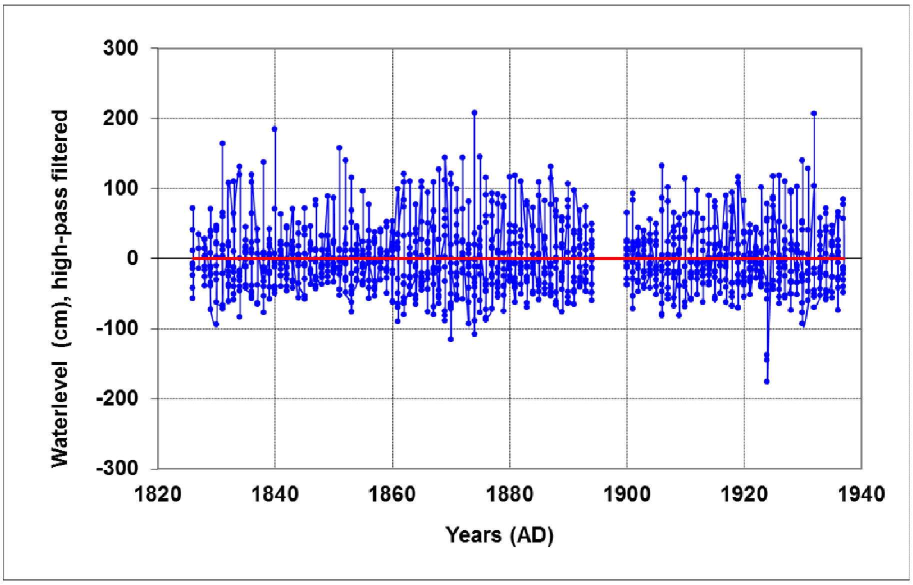


Figure 2a,b. Monthly maxima of water level (in cm) 1826 – 1937 at the gauge Ettringen/Wertach (35km south of Augsburg). a) Original data from official records, b) high-pass filtered data

In order to be able to properly understand the long-term development of flood events in the Bavarian Foreland, z-transformed 31-year running flood frequencies have been calculated in several studies (e. g. Glaser 2008, Glaser & Stangel 2003b, Böhm & Wetzel 2006, Sturm et al. 2001, Schmoecker-Fackel & Naef 2010). The 31-year time step is derived from the standard reference period of the World Meteorological Organization. This time segment is an established tool to identify the linkage of climatic coherence of time series and exhibits significant changes in flood frequencies. Although this measure results in a comparatively poor filtration effect it still meets the needs of various geoscientific approaches to define climatological phases (Schönwiese 1992).

Due to their geomorphological shapes the catchment areas of the investigated rivers have been divided in an inner- and outer-alpine region. Only the outer-alpine regions (see Fig. 1 dashed line) have been considered for the present paper. To reveal the flood sensitivity of the entire Bavarian Foreland, all flood events of the outer alpine region have been merged into one overall time series. The highest classification according to damage reports has been counted whereas local events caused by i.e. flash-floods have not been counted. Hence only mesoscale hydrological events have been incorporated into the present analysis.

In order to integrate different historical sources and locations referring to one meteorological event, a time-window including a maximum number of seven days before and after a designated event has been introduced. Therewith the varying duration of hydro-meteorological sequences (from the genesis of synoptic disturbances to the termination of flood waves) as well as the blur of historical information can be considered. For example, the summer flood of the year 1501, being one of the biggest floods since the beginning of written records (quantitative evidence in terms of a flood mark is located at the “Fischmarkt” in Passau, Bavaria), has been recorded more than 150 times in the IBT, yet it is counted only once in the 31-year running flood frequency of the Bavarian Foreland.

The determinations of flood-rich and flood–poor periods are based on a polynomial function of the 5th degree for the running flood frequencies (see black graph in Fig. 4). This method has been adapted from Glaser et al. (2004) who used polynomial functions to visualize long-term development of climatic elements. Using this function the inhomogeneity of the number of cases could best be confronted. Different databases and data densities (e. g. 14th/15th century - turn of the 15th to 16th century - beginning of the instrumental period) were thus considered as far as possible. This method does not claim precision for the beginning and the end of the defined periods but compared to a multitude of other methods and due to the changing data density over time it is the highest-performance method. Different methodical approaches with the aid of quantiles as medians or percentiles could not achieve satisfactory definitions for the generated time series and its comparability. The determined periods should come over as the results of a sensitivity analysis. The fixing of the threshold based on a polynomial function of the fifth degree coincides with the fracture points of the t-test analyses (cf. Fig. 5), so the method is provided by statistical measure.

In general, the intervals above/below the function graph are defined as flood-rich/flood-poor periods. Due to the changing data basis over the entire time series, it was necessary to interpolate in some cases (compare e.g. flood-rich period #2). With respect to the differing data density as a function of time and not as an increasing frequency in general the values in Fig.4 have been z-transformed. So the weak data density until the beginning of the 16th century is denoted by values beneath the zero line.

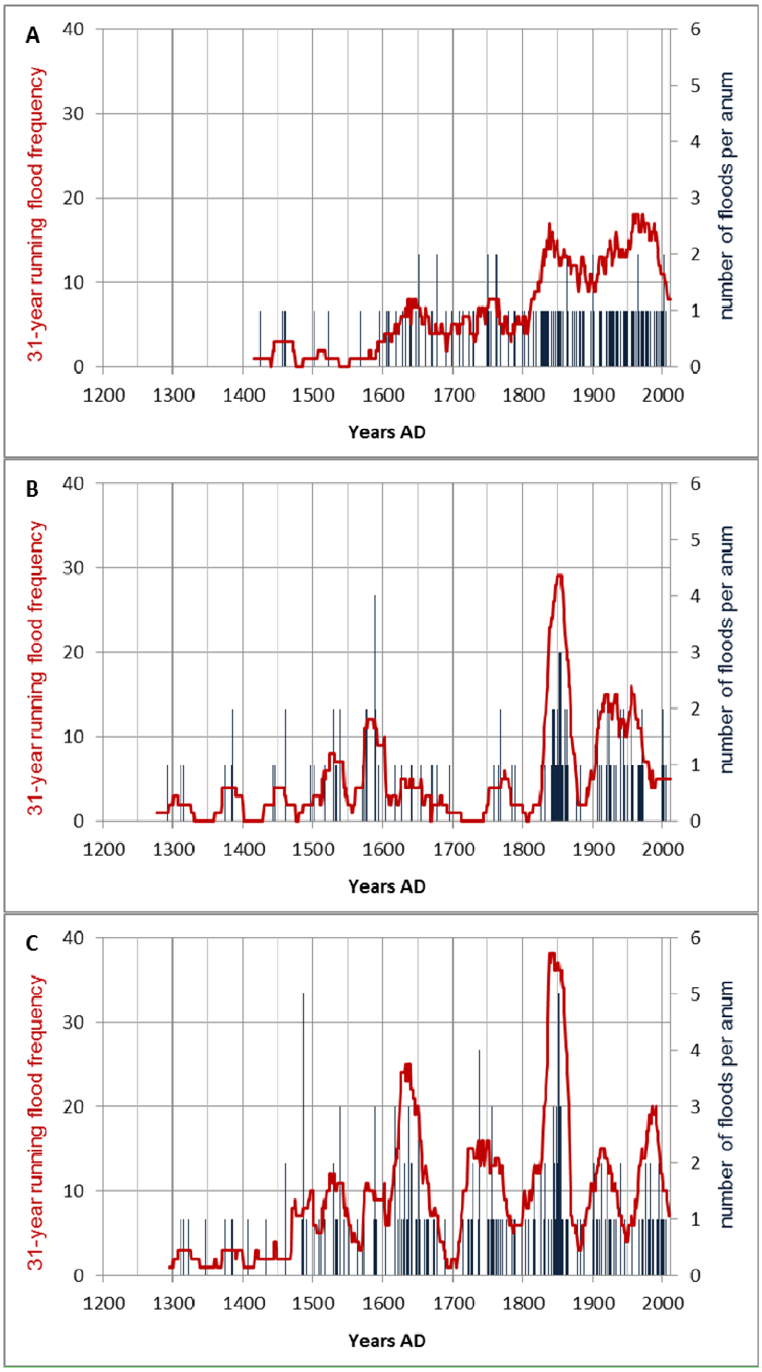
Therewith the under- and over-representative availability of data has been taken into account.
For merging the single outer-alpine time series all flood events which took place isochronally (under consideration of the above mentioned time window) have been counted only once. Virtually all counted events can be affirmed with a plurality of flood events which occurred isochronally within in the investigation area as well as in a (Central-) European context.

4.1 Statistical significance

The time series for the Bavarian Foreland has been submitted to a two-sided t-test which can identify fracture points within the time series (cf. Glaser & Stangl 2003b). The fracture points reveal differences between the means of sliding flood frequencies. The differences shown by estimators above the threshold are expected to detect significant coherence between superior framework conditions like variations of large-scale atmospheric circulation and consequential variability of flood-poor and –rich periods. The α-level of 0.05 (solid line) is depicted in Fig. 5. Most of the detected fracture points coincide with changes in atmospheric conditions (see next section). The flood frequency time series of the Bavarian Foreland has additionally been correlated with reconstructed NAO index-values (cf. Luterbacher et al. 2002a) as well as with moving mean sunspot numbers (data after Hoyt & Schatten 1997). Significant correlations between these quantities include the consideration of inherent autocorrelations (cf. Werner 2002).

5 Results

In Fig. 3 all single time series of the examined catchment areas are depicted. Taking comparability into account all axes have the same scale of values. The itemized time series of the rivers Iller (A), Wertach (B), Lech (C), Isar (D), Salzach (E) and Inn (F) are the foundation of the overall time series Bavarian Foreland depicted in Fig. 4.



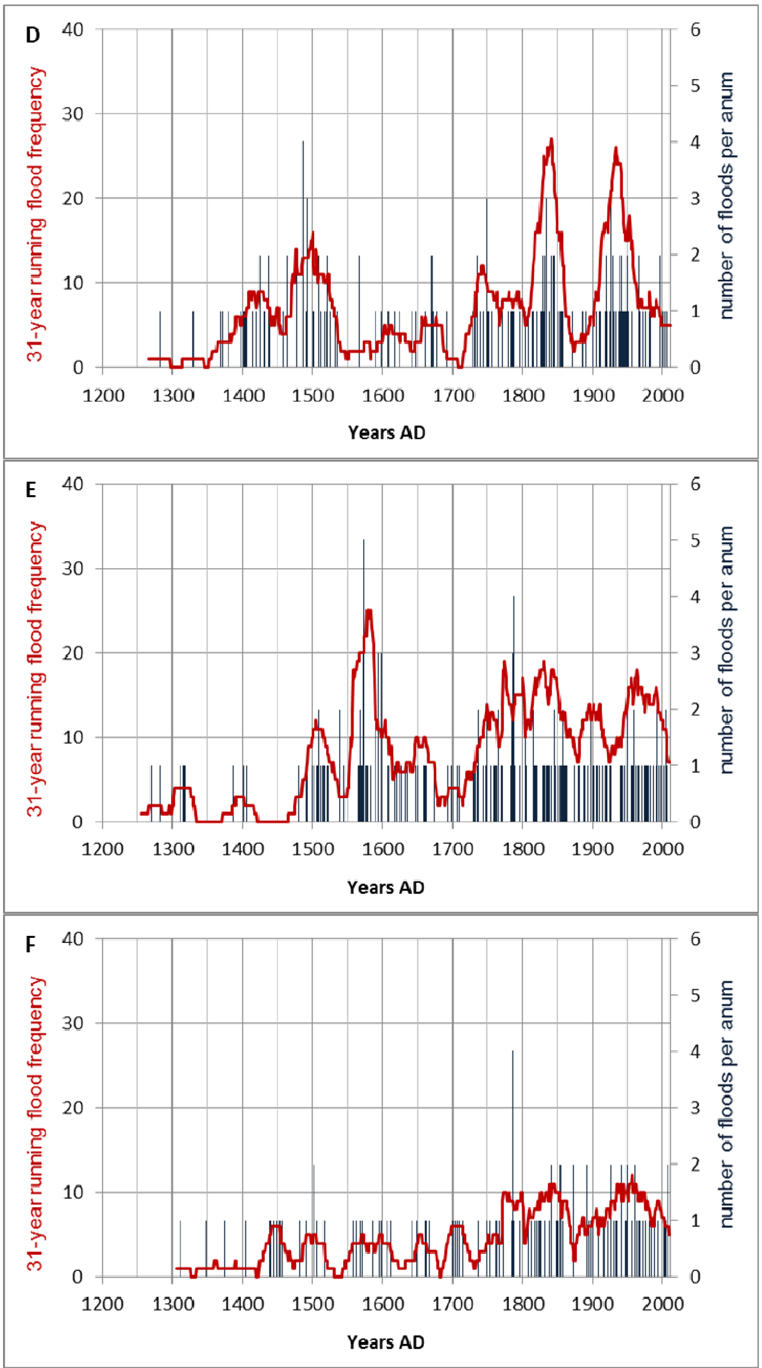


Figure 3. 31-year running flood frequencies of the Bavarian Foreland Rivers (red graph). Right ordinate: dark columns show the annual flood frequencies. A Iller, B Wertach, C Lech, D Isar, E Salzach and F Inn.

In Fig. 4 the merged flood history of the Bavarian Foreland between 1300 AD and 2010 is depicted. The data for that time series is derived from 1825 different flood records of the itemized time series (c.f. Fig. 3) which are assigned to 584 independent flood events. Based on a polynomial function of the 5th degree (see red line), 9 flood-rich and 8 flood-poor periods can be identified. Like mentioned in the methods chapter, due to changing data density over time it is the highest-performance method and the determined periods constitute the results of a sensitivity analysis. Particularly the rising data density after the mid-15th century must be seen in a context of the invention of letterpress, among other social reasons and changes. From 1826 onward measured data in daily resolution are available.

Single flood-rich periods will be discussed below. In order to prove significant changes within the time series of the 31-year running flood-frequencies of the Bavarian Foreland, we have depicted the estimators of the t-test in Fig. 5 (cf. Glaser & Stangl 2003b). In this context, changing climatic parameters like the NAO index and the sunspot numbers will be briefly approached (a more extensive discussion will follow subsequently).

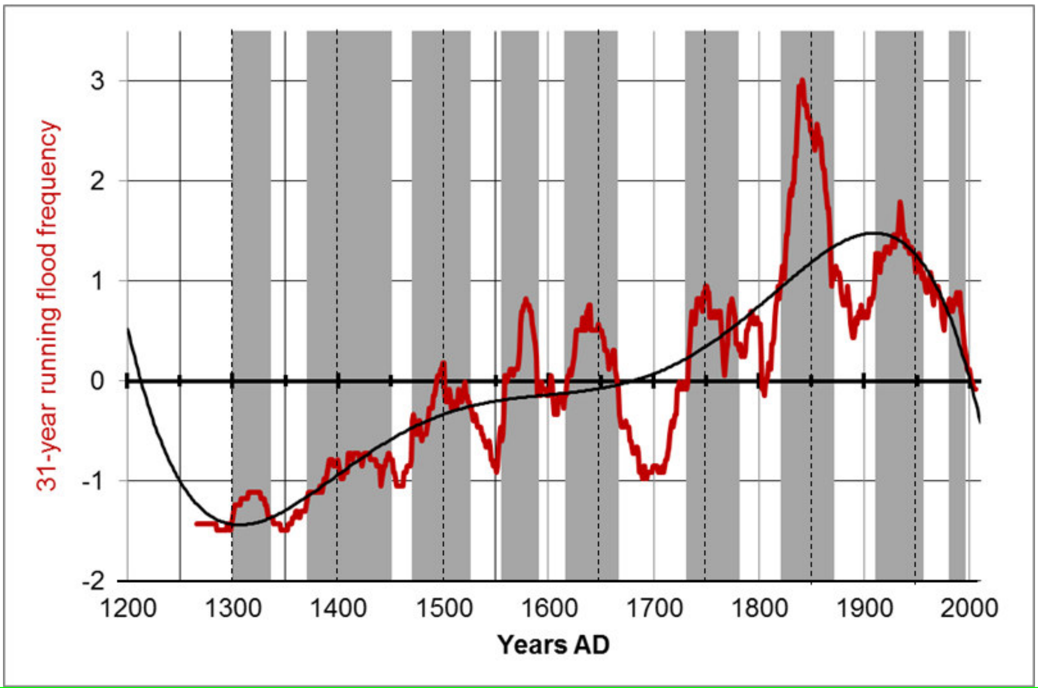


Figure 4. 31-year running z-transformed flood frequencies of the Bavarian Foreland. Grey bars label flood-rich periods #1 to #9, black graph: polynomial of 5th degree.

5.1 Flood-rich period #1: 1300 – 1335

The first flood-rich period, although based on a low data density, can be associated with changes in the atmospheric framework. Within the investigation area at least 16 records could be extracted from compilations like Alexandre (1987), different chronicles (cf. e.g. Zillner 1885, Schnurrer 1823) and the Augsburger Urkundenbuch Nr. 264 (cf. Gross 1967). Despite small data density significant changes of climatic parameters at the beginning and the end of this flood sensitive period can be stated and should not be withheld.

Wanner et al. (2000) are dating the onset of the Little Ice Age at the beginning of the 14th century, based on Miller et al. (2012), triggered by multiple volcanic eruptions. Period #1 coincides with the beginning of LIATE3, a first period of advancing glacier tongues during the Little Ice Age, additionally enhanced by the Wolf solar activity minimum (1282 – 1342, cf. Glaser 2008). Following the sunspot numbers after Usoskin et al. (2004), the first flood-rich period minutely coincides with a period of sunspot minima. According to Fig. 5, the t-test value shows significant changes with the beginning and the end of Period #1. The estimator declines during the flood-active phases (this can be verified for most of them). While LIATE3 approaches a climax, the flood frequencies decline considering a time lag due to mass input into the alpine glaciers (cf. Wanner et al. 2000). Most of the significant fracture points in Fig. 5 coincide with the beginning and the end of the flood-rich or flood–poor periods in Fig. 4. A further qualitative confirmation for particular climatic circumstances during that period is provided by Lamb (1980).

5.2 Flood-rich period # 2: 1370 – 1450

The increase of flood frequencies is accompanied by significant t-test estimators. Despite the absence of significant estimators, the end of period #2 coincides once more with changing climate conditions characterized by the beginning of the Spoerer Minimum, another sunspot minimum between the years 1450 and 1534 (cf. Glaser 2008).

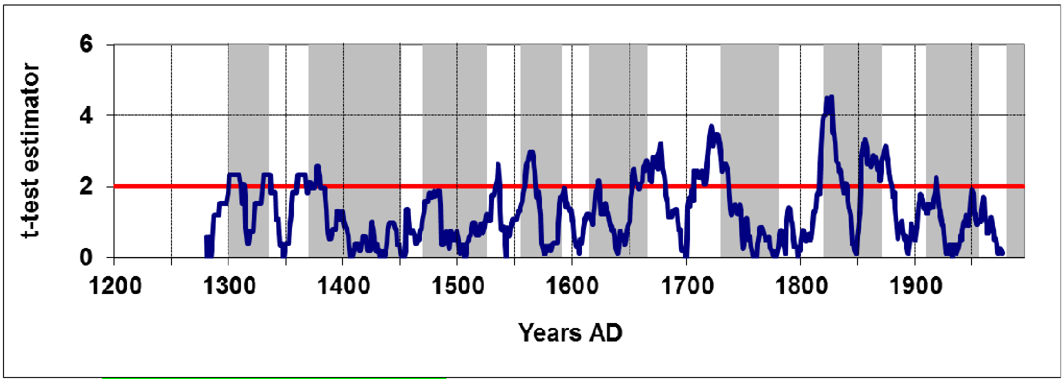


Figure 5. Differences of sliding means by 31-year running t-test estimator of flood frequencies of the Bavarian Foreland, threshold value for the two-sided t-test is 2.00 (see red line). Grey bars label flood-rich periods #1 to #9.

5.3 Flood-rich period # 3: 1470 – 1525

The transitional period between the flood-poor period #2 and the flood-rich period #3 coincides with an obviously rising estimator (significant at the α-level 0.05) as well as with the end of a distinct period of negative temperature anomalies in the Alps (cf. Wanner et al. 2000). The end of period #3 is once again marked by highly significant t-test estimator values. The maximum value is accompanied by the end of the Spoerer Minimum, again an indication for changing climate conditions which affect the flood frequencies in the Bavarian Foreland.

From 1500 onward we can use reconstructed NAO-Index (NAOI) values (cf. Luterbacher et al. 2002). The end of period #3 (= first grey bar in Fig. 6) is accompanied by an obvious declining NAOI for annual (Fig. 6) as well as summer seasonal values (Fig. 8). Due to the impact of precipitation to the entire hydrological year on flood progress, the full-year development of the NAO may reflect mean weather conditions. In general, however, the correlation between weather conditions and the NAOI is more significant during winter than during the warmer half of the year.

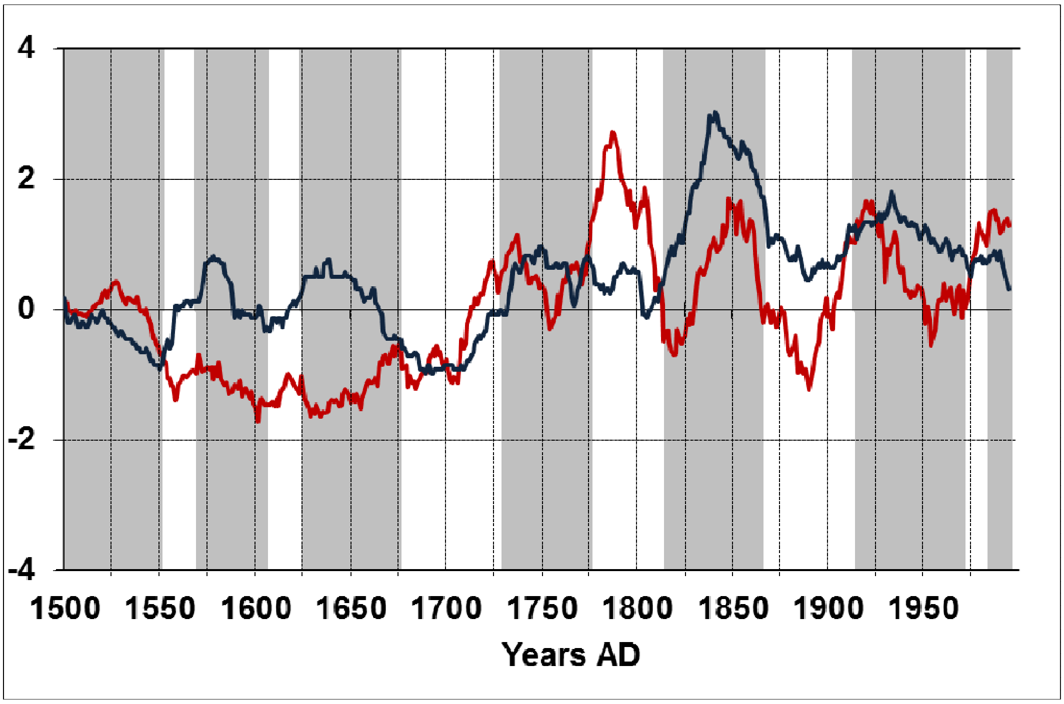


Figure 6. Z-transformed time series of annual 31-year running flood frequencies in the Bavarian Foreland (blue) and of annual 31-year running NAOI (red) (NAOI data after Luterbacher et al. 2002). Grey bars label the flood-rich periods # 3 to # 9 based on the full-year development.

5.4 Flood-rich period # 4: 1555 – 1590

Between the years 1550 and 1700 the z-transformed NAOI-values are generally characterized by low index-values. Within this period, variations in flood frequencies can be identified (see Fig. 6) with increasing and declining values being accompanied by rising and falling NAOI-values, respectively, for the whole year as well as for the seasons of winter (not shown) and summer (cf. Fig. 8). The t-test estimator indicates significant values (> 2.00 at a α-level of 0.05) at the beginning and at the end of period #4 (cf. Fig. 5). The flood frequency maximum coincides with a distinct period of negative temperature anomalies that lead into LIATE2.

5.5 Flood-rich period # 5: 1615 – 1665

Period #5 is again accompanied by significant t-test estimators for the beginning as well as for the end (see Fig. 5). The transition period between period #5 and the Maunder Minimum (1645 – 1715, cf. Schönwiese 2008) is accompanied by a conspicuous behavior of the t-test estimator, a possible evidence for unsettled atmospheric conditions. Period #5 took place during LIATE 2 (1570 – 1640, cf. Wanner et al. 2000); the retreat of the glacier tongues (peak around 1650) coincides with declining flood frequencies. Period #5 also fell into a period of declining sunspot numbers which have been directly observed for the first time since 1610 (cf. Fig 7). The absolute minima of sunspots in 1660 turned into the Late Maunder minimum and they were accompanied by the absolute flood frequency minimum from 1500 till today. With the beginning of immediate observation of sunspots we can refer to a distinct correlation between the 31-year moving sunspot numbers and flood-rich and flood–poor periods until 1930. The end of LIATE 2 coincides with the beginning of the Maunder Minimum, compare Fig. 7 and Wanner et al. (2000).

The flood frequencies are rising while the mean NAOI-values for the complete year are declining; the flood frequency peak coincides with minimal NAOI-values. The following decline of the flood frequencies is accompanied by rising NAOI-values (see Figs. 6 and 8). The development of the winter NAOI reveals a different pattern. The absolute maximum value of flood frequencies coincides with a short-termed increase of the winter NAOI. This could indicate wet winter conditions resulting in vast water retention which could favor summer floods during snow melt.

5.6 Flood-rich period # 6: 1730 – 1780

Period #6 is once again marked by significant t-test estimators during increasing flood frequencies; the end of the period is marked by a distinct evolution of the estimator values. The t-test estimators in general will not show significant variations for the next 80 years (cf. Fig. 5). Period #6 is accompanied by a noticeable development of the NAOI-values. The year-round development shows a parallel increase of flood frequencies and NAOI-values, but during the flood frequencies' peak the NAOI-values decline in a distinct way (cf. Fig. 6). The development of the Little Ice Age in terms of glacier tongue movements shows a slight stagnation.

The following flood-poor years until 1820 are characterized by a next sunspot minimum, the Dalton Minimum (1790 – 1830, cf. Schönwiese 2008), again accompanied by relatively low flood frequencies (see Figs. 3 and 4). The end of the Dalton Minimum and the beginning of the next flood-rich period is accompanied by extreme flood frequencies (cf. Fig. 4) as well as extraordinary t-test estimators (cf. Fig. 5). Reasons for that will be explained below.

5.7 Flood-rich period # 7: 1820 – 1870

Period #7 is marked by a changing database (transition between documentary period and early instrumental period). In addition, it represents the beginning of the transition period between the end of the Little Ice Age and the beginning of the Modern Climatic Optimum as well as the beginning of (systematic) anthropogenic interference into the natural river systems. Thus, period #7 falls into a section of different overlapping trends. The t-test estimators reveal this transition at the beginning of the period (unique t-test estimator values, see Fig. 5). The end of the period, based on t-test estimators, can be interpreted as inhomogeneous climatic conditions during the transition to the Modern Climatic Optimum. The increasing flood-frequencies of period #7 coincide with increasing sunspot numbers (cf. Fig. 7).

The development between LIATE1 (1810 – 1850) and period #7 requires a particular reflection, as LIATE1 and the flood-rich period end at about the same time, whereas the preceding LIATEs (# 3 and #2) did not end at the same time like the corresponding flood-rich periods. The maxima of the preceding LIATEs fall into intervals of low flood frequencies framed by the end and the beginning of flood-rich periods. A noticeably aligned development between the NAOI-values and the flood frequencies can be highlighted for the whole year as well as for the summer and winter seasons (cf. Figs. 6 and 8). The following years are characterized by both declining flood frequencies and NAOI values. In this context we can generally identify an increasing impact and significance of the summer NAOI for the development of flood frequencies in the Bavarian Foreland (discussion see below).

5.8 Flood-rich period # 8: 1910 – 1955

Period # 8 is once more framed by significant t-test estimators with a final significant estimator-value within the time series (see Fig. 5). Until 1930 similarities (or correlations) between flood frequencies and sunspot numbers do exist. After that the time series seem to be decoupled, as depicted in Fig. 7. The beginning of period #8 coincides with rising NAOI-values, the amplitude of these values in general shows a parallel development (cf. Figs. 6 and 8).

5.9 Flood-rich period # 9: 1980 – ?

A last flood-rich period starts in 1980 intersecting with the end of the time series. Due to the use of 31-year running quantities, its validity remains unclear.

5.10 The flood frequencies of the Bavarian Foreland accompanied by different climatic conditions in detail

5.10.1 The correlation of flood frequencies and sunspot numbers

The meaning of varying solar activity for the climatic conditions is currently a matter of fierce discussion (cf. Shindell et al. 2001, Feulner & Rahmstorf 2011, Feulner 2011). Generally the variability of solar activity can affect the large-scale atmospheric circulation including climate parameters like temperature, precipitation and transpiration (cf. Endlicher & Gerstengarbe 2009). Despite the uncertainty in which way solar activity could have an effect on climate development within the research area, it can be shown that solar trends (of different signs) coincide with changing climatic conditions affecting the flood frequencies in the Bavarian Foreland. Within these relationships, one certain conspicuousness must be emphasized but not discussed in detail at this point. One has to distinguish between direct observations or reconstructions based on proxy data. Both periods differ with respect to the sign of the correlation between flood frequencies and solar activity. In general, before direct observations started, high flood frequencies coincided with reduced solar activity, while then flood-rich periods coincided with increased solar activity. The best fit between the 31-year running frequencies is achieved with direct observations starting in 1610 and ending around 1930 (cf. Fig. 7). The year 1930 occupies a special position which will be discussed later on. Considering the four sun-spot minima encompassed within the investigation period, we can denote the following:

The Wolf Minimum (~ 1280 – 1340) coincides with the first calculated flood-rich period. This temporal correspondence between high flood activity and low sunspot numbers is unique within the total time series (cf. Fig. 4).

The duration of the Spoerer Minimum differs among a number of authors. According to Glaser (2008), the Spoerer Minimum takes place between the years 1450 and 1534, whereas Schönwiese (2008) identifies the years 1400 – 1510. According to the first definition of the Spoerer Minimum, another sunspot minimum coincides with a flood-rich period (here period #3). Keeping with the sunspot data of Usoskin et al. (2004), the flood frequency maximum of period #3 also corresponds to the low sunspot numbers of the Spoerer Minimum.

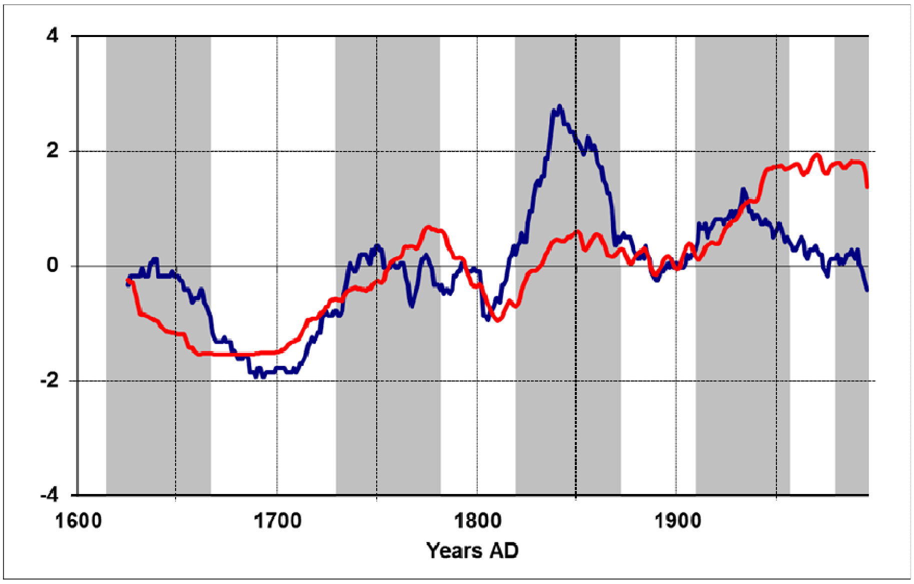


Figure 7. Z-transformed time series of annual 31-year running flood frequencies in the Bavarian Foreland (blue) and "sunspot activity" (red) since 1610 (Data for sunspot activity modified after Hoyt & Schatten 1997). Grey bars label the flood-rich periods # 5 to # 9 based on the full-year development.

With the beginning of the Maunder Minimum period the indication of the relationship changes. As depicted in Fig. 7 running flood frequencies and sunspot numbers are varying in a similar way. The course of both graphs during the Dalton Minimum (1790 –1830) again shows a similar development. These data indicate a significant trend, between the years 1610 and 1995 the Pearson correlation coefficient amounts to 0.62, between 1700 and 1930 to 0.7. Autocorrelation could be achieved by using the effective sample size based on a method by Werner (2002), which regards the statistical persistence of database-inherent autocorrelations ($\alpha = 0.01$). After 1930, the relationship of sunspot numbers and flood frequencies seems to be decoupled. A comparison of global temperatures and GAR (Greater Alpine Region) temperatures shows a temperature leap over the calculated neutral-point temperature development since the beginning of the early instrumental period (cf. Auer et al. 2007).

Not all flood-rich and flood-poor periods can be connected to sunspot minima or maxima, but all sunspot extremes can be connected to changes of overall climatic conditions irrespective of its trends (cf. Böhm 2011)

5.10.2 Correlations of flood frequencies and NAOI-values in detail

Is it possible to associate (in a statistical sense) the variability of the NAO and the flood history of the Bavarian Foreland? Due to oscillations of barometric pressure between the so called Island cyclone and Azores anticyclone weather conditions of the investigated area can be affected in various manners. Based on the reconstruction of the NAOI by Luterbacher et al. (2002), the time series of the flood frequencies (31-year running mean values) and of the NAOI (likewise 31-year running mean values) can be compared from 1500 AD onward (cf. Figs. 6 and 8). The NAO is one of the dominating teleconnection patterns regulating the regional characteristics of many climatic parameters. The NAO also reveals seasonal variations (in context of the climatic seasonal cycle).

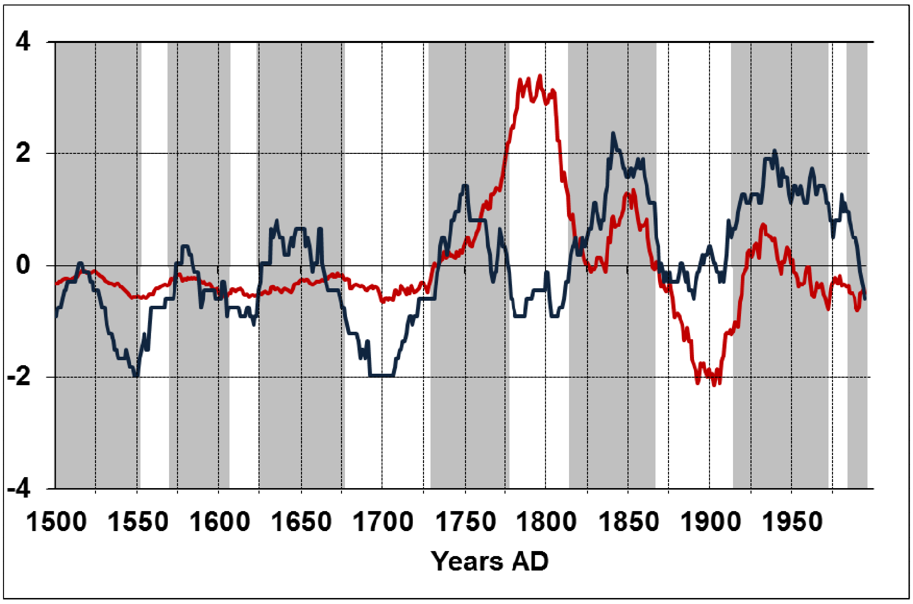


Figure 8. Z-transformed time series of 31-year running flood frequencies in the Bavarian Foreland (blue) and NAOI values (red) for the meteorological summer (JJA) (NAOI data after Luterbacher et al. 2002). Grey bars label the flood-rich periods # 3 to # 9.

The annual and the summer time series of flood frequencies and of NAOI-values have been compared. The confrontation of the annual valuables is depicted in Fig. 6, the comparison for the summer seasonal in Fig. 8. The particular importance and the general dominance of summer floods in the Bavarian Foreland were already accosted. The winter flood occurrences are mainly relevant in terms of the retention potential of the alpine catchment areas which supports the development of floods in general. In spite of the general decline of the NAO importance during summer, significant correlations of the NAO (-index) and the time series of summer floods can be recognized. In a first step 100-year intervals have been considered. For the centuries 1500 – 1599 ($r = 0.78$, $\alpha = 0.01$) and 1900 – 1999 ($r = 0.65$, $\alpha = 0.01$) significant correlations occur (once again verified by the calculated persistence). Shifting the time-interval by 50 years, a significant correlation can be observed for the period 1650 – 1749 ($r = 0.8$ Furthermore, the years from 1830 to 1999 exhibit another highly significant correlation coefficient of $r = 0.8$ ($\alpha = 0.01$). The changing sign in the relationship around 1820 (cf. Fig. 8) coincides with the important transition period between the Little Ice Age and the Modern Climate Optimum.

5.11 The flood frequencies of the Bavarian Foreland in confrontation with selected flood frequencies of Central Europe

This confrontation is limited to the period between 1500 and 1900. The limitations result from weak data density in general before 1500 and in a multitude of anthropogenic overprints of the river systems around the beginning of the 20th century. The comparison will be limited to the Lower Rhine and Middle Rhine (cf. Glaser 2008), the Vlatva (an Elbe tributary) and the Czech Elbe itself (cf. Brazdil 1998). The confrontation is depicted in Table 4. Due to the decadal visualization of beginnings and endings of the marked periods they underlie a certain blur. Similarities for all time series can be particularly highlighted for the second half of the 16th century. In general an unexpected similarity can be stranded between the time series of the Bavarian Foreland and the Lower Rhine, except the years 1790 until 1819. Good accordance between the Bavarian Foreland can be revealed for the first and seventh and eighth decade of the 16th century. During the 17th century only the sixth decade shows good accordance. A further good accordance can be highlighted for the end of the 18th and beginning of the 19th century. Reasons for this variable behavior are founded in the variability of general synopsis and resulting weather conditions. In that context the above mentioned NAO is playing a vital role. For a further understanding of the variability between the confronted time series meteorological aspects must be consulted.

Table 4. Confrontation of selected flood frequencies. Lower Rhine (RHl), Middle Rhine (RHm), Czech Elbe (ELBcz), Vlatava (VLA) and Bavarian Foreland (BF). Due to the decadal visualization beginnings and endings of the marked periods underlie a certain blur. Data altered according to Glaser (2008) and Brazdil (1998).

	RHl	RHm	BF	ELBcz	VLA	
1500						1500
1510						1510
1520						1520
1530						1530
1540						1540
1550						1550
1560						1560
1570						1570
1580						1580
1590						1590
1600						1600
1610						1610
1620						1620
1630						1630
1640						1640
1650						1650
1660						1660
1670						1670
1680						1680
1690						1690
1700						1700
1710						1710
1720						1720
1730						1730
1740						1740
1750						1750
1760						1760
1770						1770

1780						1780
1790						1790
1800						1800
1810						1810
1820						1820
1830						1830
1840						1840
1850						1850
1860						1860
1870						1870
1880						1880
1890						1890
1900						1900

6 Conclusions

The flood history of the Bavarian Foreland could be analyzed in a statistical way from the beginning of the 14th century onward (based on the existing data). The flood history of the entire Bavarian Foreland was compiled and analyzed, based on both documentary and instrumental data. We could identify statistical correlations between the flood frequencies and conditions of the atmospheric framework up to today based on different climate proxies and historical observations and transmissions.

The investigation period commences amid the latest climatic depression of the Subatlantic stage (2.5 ka – present) until today. Despite the reduced availability of data at the beginning of the time series including the absence of reconstructions of pressure fields, temperature and precipitation (until 1499), significant changes in the correlation between climate conditions and flood frequencies can be identified. Virtually each shift in the flood frequencies' trend (towards flood-rich or flood-poor periods) coincides with significant fracture points within the time series (according to two-sided t-tests). These fracture points provide indications of changing atmospheric conditions which may affect the flood development in general.

The NAO is of particular importance for the climatic conditions in the Bavarian Foreland as well as in the Alps in general. However, according to Casty et al. (2005), the NAO alone cannot explain the very sophisticated climatic events of the Greater Alpine Region (GAR). The present work describes multiple mechanisms with influences to major atmospheric conditions. With a view towards the changing directions of the flood frequencies the shifts themselves within multiple climatic factors are playing an important role in the climatic circumstances of flood development. In this context, the dominant role of the summer NAO from 1830 onward is conspicuous. This atmospheric parameter coincides with the beginning of the transition period between Little Ice Age and Modern Climate Optimum. Until the end of the time series, high correlation coefficients do exist. For this special period a statistical unique coherence within the present work can be emphasized.

Another remarkable influence on flood frequency development might come from solar activity. Despite marginal changes of global radiation, the correlation between flood frequencies and sunspot numbers from 1610 until 1930 is rather high. For the Maunder Minimum, the solar radiation was merely reduced by about 0.24 % (compared with the present mean value, cf. Lean & Rind 1998). This causes a cooling effect of 0.5° C at the most for the northern hemisphere. Seemingly, the slight change of solar radiation should lead to a significant alteration of atmospheric fluxes, particularly concerning the moisture content of air masses. Nevertheless, the high correlation between flood frequency and solar activity cannot explain the mechanism of action from the solar surface through the atmospheric stories towards the surface. To explain this mechanism of action further investigations are necessary.

After the year 1930, the natural relationships seem to be superimposed by an increasing anthropogenic influence on the climatic conditions. In this context a decoupling of a retrograde signal could be revealed. That assumption will be indicated by trespassing the threshold of the average temperature deviation for the GAR in 1930 (cf. ZAMG 2011).

The current report emphasizes the importance of long time series. The complexity of northern hemispheric (or even global) circulation dynamics as well as the range of natural climate variability is, however, only partially understood.

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