EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **41**, 1266–1275 (2016)

(wileyonlinelibrary.com) DOI: 10.1002/esp.3953

The influence of hydroclimatic variability on flood frequency in the Lower Rhine

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Received 23 May 2015; Revised 17 March 2016; Revised 16 November 2015; Accepted 24 March 2016

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: Climate change is expected to significantly affect flooding regimes of river systems in the future. For Western Europe, flood risk assessments generally assume an increase in extreme events and flood risk, and as a result major investments are planned to reduce their impacts. However, flood risk assessments for the present day and the near future suffer from uncertainty, coming from short measurements series, limited precision of input data, arbitrary choices for particular statistical and modelling approaches, and climatic non-stationarities. This study demonstrates how historical and sedimentary information can extend data records, adds important information on extremes, and generally improves flood risk assessments. The collection of specific data on the occurrence and magnitude of extremes and the natural variability of the floods is shown to be of paramount importance to reduce uncertainty in our understanding of flooding regime changes in a changing climate. For the Lower Rhine (the Netherlands and Germany) estimated recurrence times and peak discharges associated with the current protection levels correlate poorly with historical and sedimentary information and seem biased towards the recent multi-decadal period of increased flood activity. Multi-decadal and centennial variability in flood activity is recorded in extended series of discharge data, historical information and sedimentary records. Over the last six centuries that variability correlates with components of the Atlantic climate system such as the North Atlantic Oscillation (NAO) and Atlantic Multi-decadal Oscillation (AMO). These climatic non-stationarities importantly influence flood activity and the outcomes of flood risk assessments based on relatively short measurement series. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: Rhine River; Atlantic Multi-decadal Oscillation; North Atlantic Oscillation; non-stationarity; climate change; flood risk assessments

Introduction

Recent and anticipated future anthropogenic-induced climate change is expected to cause increased occurrence and severity of extreme weather events in Western Europe [Intergovernmental Panel on Climate Change (IPCC), 2012; KNMI (Royal Netherlands Meteorological Institute), 2014]. For this region, it is expected that during winters the intensity of precipitation events and related flash-flooding in upstream (sub-)catchments will increase, while longer periods of drought are expected during summers (Feyen *et al.*, 2012). This could have a significant effect on river discharge regimes and associated risks, including flood-related damage to urban areas and infrastructure, and reduced navigability during summer droughts. For the Lower Rhine, the region's largest river system (Figure 1), studies project a more frequent occurrence of large floods in the future, potentially exceeding the discharges of events-of-record of the last century (de Wit *et al.*, 2007; Bakker and te Linde, 2008). Current safety levels along the Dutch Rhine channels are set to protect against a flood with a statistical re-occurrence interval of 1250 years with an estimated discharge of ~16 000 $\mathrm{m^3\,s^{-1}}$ (Parmet *et al.*, 2001; Silva *et al.*, 2001), while the largest flood of the last century (AD 1926) reached only ~12 600 $\mathrm{m^3\,s^{-1}}$. To assess the potential effects of climate change the Dutch government (Delta Programma, 2014) has initiated a 20-billion Euro flood safety investment plan (~1 billion per year up to 2028, of which one third will be spent on the Rhine system specifically). In view of potential future climate change impacts on Rhine discharge, a peak discharge of 18 000 $\mathrm{m^3\,s^{-1}}$ has been recommended as a design discharge to adopt in the near future (Vellinga *et al.*, 2009; Delta Programma, 2014).

Predictions regarding the future flooding regime of the Lower Rhine (used in the Delta Programma) are currently based exclusively on general regional climate predictions, on statistical methodologies and analysis, and on hydrologic modelling. In recent years, major advance in flood risk assessment has been obtained using a stochastic weather generator in combination with runoff and flood propagation modelling (e.g. GRADE 2.0 project; Hegnauer *et al.*, 2014; Table I). This method is a considerable improvement compared to using standard statistical extrapolation from just short measured data series alone, but the stochastics of the simulated events still depend on relatively short input data series (~ 50 years) and the further calculation of discharge magnitudes suffers from that data limit too. The runoff

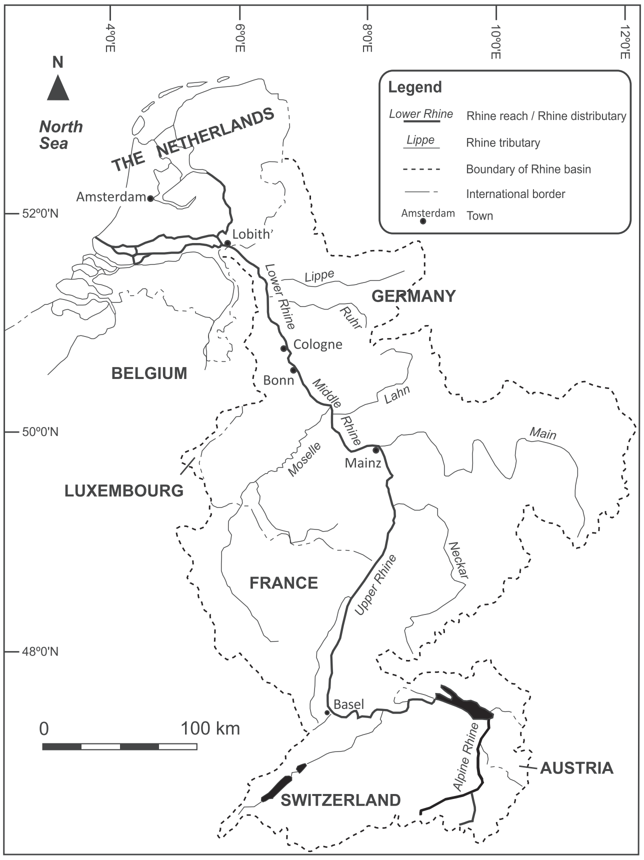

Figure 1. Catchment of the River Rhine.

and flood propagation modelling part, for example, cannot be calibrated in the range beyond the largest measured flood, while sensitivity analysis of the calibration suggest a 'non-monotonicity' in the meteo-hydrological behaviour of the catchment in that range (Hegnauer *et al.*, 2014). Moreover, current projections of future flooding regimes rarely consider the physical properties of catchments, nor do they routinely incorporate natural variability such as multi-decadal climatic non-stationarities (Toonen, 2015).

In the Lower Rhine, severe flooding generally occurs between January and March. Their peak discharges are generated by a combination of three hydro-meteorological conditions: heavy rainfall over impermeable saturated soils of major sub-catchments (Moselle, Main and Neckar; Figure 1) in central and southern Germany, combined with extensive snowmelt over frozen soils in these same regions (with thick accumulated snow stacks from severe winters), adding up to snowmelt and glacier runoff released from Alpine sub-catchments at distance further south (e.g. Disse and Engel, 2001; Middelkoop *et al.*, 2001). In contrast to the aforementioned near-future expectations of increased precipitation and flash flooding, Kundzewicz *et al.* (2006) stressed that as winter temperatures are getting higher and will hamper stacked snow accumulation, early spring floods induced by snowmelt are likely to reduce in magnitude and frequency. Climate change could therefore affect main discharge-generating factors for larger floods in the Lower Rhine in opposite ways.

The size and physiography of the Rhine catchment is also of importance, as the northern part and southern parts of the catchment demonstrate rather opposite modes of flood activity, in line with the larger climatic zonation in Western Europe in response to Atlantic storm track configuration and temporal changes therein (e.g. Marshall *et al.*, 2001; Magny *et al.*, 2003; Mudelsee *et al.*, 2004; Dankers and Feyen, 2009; Foulds *et al.*, 2014; Hall *et al.*, 2014; Schulte *et al.*, 2015). The trunk valley of the Rhine crosses these zones in a north-westward direction, building up a cumulative flooding regime from sub-catchments with mixed responses to changes in storm track configuration and general climate change. Changes in individual upper catchments are thus expected to be heterogeneous and could differ from the general change in flooding regime down the trunk valley.

The factors discussed earlier complicate the assessment of the frequency at which extreme discharge events will be triggered under future climates. Whereas for the Lower Rhine it is reasonably understood how climate change can affect the normal discharge regime (and hence river navigation and water demands; Kwadijk and Middelkoop, 1994; Middelkoop *et al.* 2001; Te Linde *et al.*, 2010), it remains unclear how it will affect the frequency and peak discharges of extreme floods, and thus whether currently-set design standards are justified and supported by the right information.

To tackle the sensitivity and uncertainty issues in the assessment of extreme-event recurrence, historical and sedimentary information on past floods is required to extend the flood series (e.g. Kjeldsen *et al.*, 2014). Although the precision of such alternative information is usually lower than twentieth and twenty-first century data, it can be particularly useful in the realm of extreme floods (Kochel and Baker, 1982), which modern records of limited length tend to represent poorly (Klemeš, 2000). In the last few years, a series of papers documented and correlated temporally overlapping sedimentological, historical and modern-observational information of Lower Rhine floods (overview in Table I). This paper proceeds on these individual studies and further assesses and integrates their results to provide hydrological and climatological understanding of the Lower Rhine flooding regime. The aim of this paper is to strengthen the region's flood risk assessments and choices of design flood levels for the coming decades. First by assessing the current status of flood frequency analysis, and second by identifying important trends in flood activity and the occurrence of extreme events.

A comparison between previous flood risk assessments and compiled sedimentary and historical data series is used to demonstrate the strength of adopting an ensemble consideration of various records for flood risk assessments. Explanations for the differences between flood risk estimates based on various data types are mainly sought in (natural) non-stationarity of flooding regimes, by looking at the length and phasing of periodicities in flood intensity indices, and to compare these with important climatic mode-shifts in the region, notably of the North Atlantic Oscillation (NAO) and Atlantic Multi-decadal Oscillation (AMO).

This Lower Rhine case study showcases a holistic strategy to quantify hydroclimatic variability, using data derived from multiple sources to assess hydroclimatic change and associated flood risk in the downstream region of a relatively complex and large catchment. This proceeds on previously developed methodologies for assessing flood risks using sedimentary and historical information (e.g. Baker, 2008; Benito *et al.*, 2004; Kjeldsen *et al.*, 2014), and integrates such information for the lower reach of an alluvial river with evidence for climatic non-stationarity.

Materials and Methods

Various types of flood data, that can be deployed to review the current status of flood risk assessments, are available for the Lower Rhine region. Previous studies range from statistical exercises to interpretation of historical records and flood magnitude reconstructions based on sedimentary records. Here, we bring together these different data types to compare their

Table I. Overview of Lower Rhine flood data series.

Range	Type of flood data and methodologies	References
Data series approach: *use of modern observational series, historical and sedimentary records.*		
AD 1901–1996 AD 1901–2002	Statistical extrapolations (Generalized Extreme Value or Gumbel rating curves) using annual peak discharge series from the Lobith monitoring station.	Silva *et al.*, 2001 Chbab *et al.*, 2006
AD 1772–2012	Statistical extrapolation, using the GEV approach, using annual peak discharge information from the Lobith monitoring station combined with discharge reconstructions based on regional water level series since AD 1772.	Toonen, 2015
AD 1550–2012	Peak discharges of historical floods exceeding bankfull levels reconstructed from sedimentary information of flood units. The grain size of individual beds located in an infilled oxbow (Toonen *et al.*, 2012) and a dyke breach scour hole located in the direct vicinity of Lobith (Figure 1) were calibrated on modern discharge series and used to infer discharges of historical floods. Recurrence time estimates for moderate to large events were based on a combination of sedimentary information and monitored discharge data after 1901. The range in estimates (plotted in Figure 2) is based on the difference in outcomes from the two study locations.	Toonen *et al.*, 2015
AD 1350–1772	Flood damage described by historical records was scored according to intensity classes, based on the severity of the event and regional extent. This by-proxy flood data was averaged in a 31-year window to describe changes in flood intensity. Discharge information after AD 1772 was converted to the same intensity classes, based on the estimated recurrence times and associated discharge of each class.	Toonen, 2015
Weather generator approach (*GRADE 2.0*)		
AD 1951–2006	Hydrological modelling of Lower Rhine floods based on meteorological data since 1951, which was stochastically resampled for 50,000 data points and coupled with a runoff model to simulate peak discharges. Present dyke heights and floodplain configuration was used to simulate the effect of upstream floodplain inundation and dyke breaches on Lower Rhine peak discharges. This introduces a physically correct upper limit to discharges that can be propagated downstream in the current Lower Rhine Valley setting.	Lammersen, 2004 Hegnauer *et al.* 2014
Individual extreme event reconstructions		
AD 1374	Largest flood identified in historical and sedimentary records of the Lower Rhine. The maximum possible peak discharge at Lobith of ~18 000 m^3 s^{-1} was modelled using historical flood markers from Cologne (Germany). The estimated recurrence time of this event is based on the relative coarseness of flood deposits; it is the coarsest flood unit recorded over a period of more than eight millennia.	Buisman, 1996 Herget and Meurs, 2010 Van Doornik, 2013 Toonen, 2013
c. 4.7 ka BP	Palaeodischarge and recurrence time calculations for a flood that occurred around ~4.7 ka BP, which has been preserved as a slackwater deposit (Baker, 2008) in an organic channel fill on an Early Holocene fluvial terrace level at ~5 m above the modern river (~25 km upstream of Lobith). In 10 scenarios a Chézy-based slope–area calculation for the prehistorical situation was used to calculate a best guess for the palaeodischarge of this event. The result was corrected for major deforestation and river training using numerical model outcomes for land-use changes in the Rhine catchment.	Toonen *et al.*, 2013 Minderhoud *et al.*, 2016

results, with a focus on the registration of rare high-magnitude events. Table I provides a concise overview of the followed methodologies and main results of each individual study – for specific details we refer to the original publications.

To explain the differences in flood recurrence-magnitude estimates between the various studies and data sets, periodic fluctuations in the occurrence of floods were analysed. Periodicities in flood activity were analysed from discharge measurement series, historical flood series derived from damage reports, and sedimentary data. The results were compared with past variations in NAO and AMO to explore: (i) whether these components of the Atlantic climate system could be important drivers for the observed variability in flooding, and (ii) what the effect of periodic variations in flood activity might be on the outcome of flood risk assessments based on records of various length.

Available data types for Lower Rhine flood frequency analysis

Flood risk is usually based on the frequency–magnitude analysis of observed discharge time series. As systematically recorded annual peak discharge series are generally relatively short (covering the last century), the discharges of low-probability high-magnitude events are usually estimated by statistical extrapolation of the inferred frequency–magnitude relation. Ideally, such exercises should carefully assess the choice of the statistical function that describes this relation (Chbab *et al.* 2006), include the precision of the input data (Toonen, 2015), and screen for effects of climatic and human non-stationarity (Knox, 2000; Milly *et al.*, 2006; Machado *et al.*, 2015). That full array of uncertainties is, however, rarely considered.

In this study we combine and compare several outcomes of regular flood frequency analysis (statistical extrapolations) with historical and sedimentary information and the results of hydraulic modelling, to mutually value the results of various disciplines. Four discharge series extrapolations (one based on synthetic discharge series generated with a stochastic weather generator; Table I), all for the Lobith monitoring station (Figure 1), were used to illustrate the spread in outcomes that follow from the use of various lengths of modern discharge series and different statistical approaches in traditional statistical frequency–magnitude extrapolations (Table I). Sedimentary information gathered from an abandoned channel-fill sequence and the sedimentary infill of a dike breach scour hole, spanning the last ~450 years (Toonen *et al.*, 2015), provided a range of historical flood discharge estimates based on the coarseness of well-preserved individual flood units (Table I). This sedimentary data series was used to independently calculate the recurrence times of moderate to large floods (10 000–14 000 $m^3 s^{-1}$) over a longer reference period.

For the assessment of extreme events, in the domain of a millennial recurrence time where uncertainty is largest and traditional statistical extrapolations diverge most, a combination of sedimentary data, historical information, and hydraulic modelling was used to constrain the outcomes of traditional flood frequency analyses. To explore the very upper end (or limit) of Lower Rhine discharges that possibly reached Lobith in the past, discharge reconstructions using historical flood-level markers of the catastrophic AD 1374 Cologne flood (Herget and Meurs, 2010) were combined with recent flood wave propagation modelling of the same event (van Doornik, 2013). The same event was identified in sedimentary palaeoflood archives as the largest event of the last *c.* 8000 years (Toonen, 2013) – this provided a recurrence time for the estimated historical discharge. The estimated AD 1374 discharge was compared with the results of a model study in which the physical limit to discharges that can be conveyed downstream (in the past and current setting; Lammersen, 2004) was explored systematically. This provided an independent reality check on high-end discharge reconstructions. Before the availability of reliable historical records (AD 1350), an independent study of slackwater deposits, dated to 4.7 ka BP (Table I) and located on a relatively high fluvial terrace in the Lower Rhine Valley, produced a discharge estimate and recurrence time for a second extreme event.

All recurrence-magnitude data points and extrapolation curves were combined in a single plot to visualize the spread in outcomes using different approaches and is intended as supportive information to discuss the quality of various flood frequency analyses. The ensemble presentation of the various data allows discussion of the effects of climatic non-stationarity on the flooding regime, and its effect on the outcomes of flood frequency analysis – especially when data series of different lengths are used.

Stationarity analysis

To determine periodicities in the occurrence of floods, we applied a wavelet analysis on three independent data sets (Table I); the Lower Rhine annual peak discharge series from AD 1772–2012, historical flood information since AD 1350 with flood magnitudes scored according to flood intensity classes (based on reported damage; Toonen, 2015), and flood series based on discharge reconstructions from sedimentary flood unit grain size since AD 1550. Using a simple Fourier transform on all records, main periods of variability were established to range between 4 and 128 years. This information was used as input for wavelet analysis to focus on this specific interval. Following the methodology of Torrence and Compo (1998), the data sets were first normalized and notch-filtered before analysis using a Morlet wave.

In an attempt to identify the main climatic drivers for the observed non-stationarities, the phasing of flood-intense versus flood-poor intervals was compared with oscillations of the Atlantic climate system. The focus was on North Atlantic storm tracks and patterns in winter precipitation, which are presumably the main mechanisms for generating large Lower Rhine floods. A visual comparison between climate indices and Lower Rhine historical flood activity was supported by simple linear regressions to establish the correlation between the various data sets. Monthly climate data series were downloaded from KNMI Climate Explorer (www.climexp.knmi.nl), and smoothed over a 30-year window for correlation. The correlations could indicate possible links but do not necessarily provide a complete explanation of flood forcing mechanism and regional conditions that triggered large floods in specific years. The general timing of extremes and the phasing of identified non-stationarities in general flood activity were compared with indices for climatic variability to discuss the timing and forcing mechanism for extreme events. This adds to the current debate on the relation between (anthropogenic) climate change and a possible increase in (and clustering of) extreme events in the last decades (e.g. Milly *et al.*, 2002; Mudelsee *et al.*, 2003; Foulds and Macklin, 2016).

Results

Flood frequency analysis; systematic and non-systematic flood data

Statistical extrapolations of systematic data series (Table I) have relatively great variance (Figure 2). The variation in outcomes is caused by the different lengths and periods covered by the data series and the various statistical approaches (Table I). Consideration of reconstructed discharge data back to the late eighteenth century, with the inclusion of an anomalously flood-poor interval between AD 1883–1920 (Toonen, 2015), results in significant lowering of the discharges associated with longer recurrence intervals compared to other studies exclusively based on more recent data (Figure 2). However, both the (short) high and the (long) low-end series have their drawbacks. In general, short series perform poorly in probability estimates of rare high-magnitude floods (Klemeš, 2000), while longer series may introduce data that is not representing the current flooding regime due to human and climatic non-stationarities (Machado *et al.*, 2015; Toonen, 2015). The extrapolation of the synthetic-resampled data series of the GRADE2.0 project gives an intermediate outcome. Hegnauer *et al.* (2014) mention their input data series to include a relatively flood-prone decade, and identified a rising effect on outcomes using jack-knifing sensitivity tests.

Independent non-systematic flood data, drawn from historical and sedimentary archives, all plot within the 90% uncertainty envelopes of the 1901–1996 flood frequency–magnitude curve (Figure 2), but there are some important considerations. Sedimentary information derived from in-filled oxbow lakes (Toonen *et al.* 2012; Toonen *et al.*, 2015) plots recurrence times of moderate to large floods near the lower estimates of the 1901–1996 extrapolation, but still higher than the extrapolation based on the longer 1772–2012 series. For extreme floods with a recurrence time exceeding a millennium, information from slackwater deposits of Middle Holocene age indicates discharges exceeding 14 000 $m^3 s^{-1}$ (Toonen *et al.*,

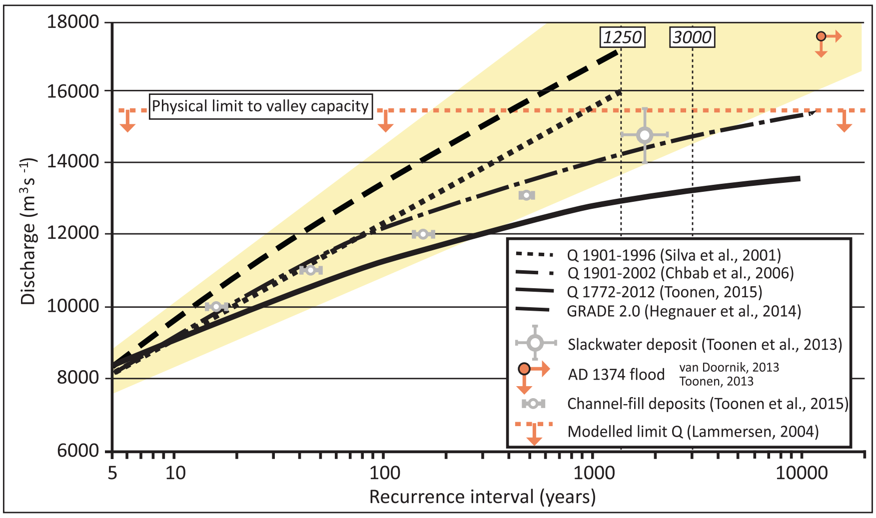

Figure 2. Flood frequency analysis of systematic flood data combined with non-systematic historical and sedimentary information, and outcomes of numerical modelling exercises focusing on maximum Lower Rhine peak discharges. The 90% confidence interval of the 1901–1996 discharge data extrapolation (Silva *et al.*, 2001) is indicated in a light-yellow shade. Dashed vertical lines indicate current (1250 year) and future (*c.* 3000 year) design flood return times.

2013). Hydraulic modelling experiments of the AD 1374 flood suggest a peak discharge of ~18 000 $m^3 s^{-1}$ to have reached the Lobith station (van Doornik, 2013). This estimate is to be considered a maximum discharge, however, because downstream flood discharge loss by overtopping of valley shoulders was not accounted for in the model that was used. Lammersen (2004) simulated Lower Rhine maximum discharge waves of ~15 500 $m^3 s^{-1}$ for the modern embanked river, and showed an overtopping peak-discharge reduction effect at that magnitude. Only considerable rising of dykes along the German reaches of the Lower Rhine would increase downstream conveyance in the future – in that case a rare 18 000 $m^3 s^{-1}$ might carry from Cologne downstream to Lobith (Figure 1).

Although the non-systematic data differs greatly in type, continuity-of-coverage and reach back in time (Table I), the compilation of data points shows that their independent results correspond. This suggests that, in ensemble with the systematic series, they can be used to quantify flood return times over timeframes longer than the last century and/or centuries other than the last century. A flood frequency–magnitude rating curve based on the compilation of non-systematic data points would plot lower than previous estimates, so lower probabilities are associated with large discharges than previously assumed based on the last century observations. It plots higher, however, than the flood frequency–magnitude rating curve constructed on the longest length systematic series (1772–present). Figure 2 thus visualizes the dependency of flood frequency analysis outcomes on the timeframe chosen for the analysis, and suggests that non-stationarity of the flooding regime produces different results when different intervals are considered. The non-systematic data corresponds remarkably well with the GRADE2.0 results, which may reflect correct assumptions regarding physical constraints used in this modelling approach.

Non-stationarity and the occurrence of extreme events

The twentieth century was marked by relatively frequent and large floods, leading to high-end extrapolations and a likely overestimation of low-probability >1000-year discharges (Figure 2). Historical data indicate that flood activity has periodically varied since the fourteenth century (Toonen, 2015). Wavelet analysis of the various data series (measured observational data, historical by-proxy flood series derived from damage reports, and sedimentary data; Table I; Figure 3) similarly indicates important variability in flood occurrence. The annual peak discharge series since 1772 (Figure 3A) shows a strong 32–40 year periodicity; especially in the 1825–1975 window, and consistently showing outside that window too, although not exceeding a 95% confidence level. Over shorter time intervals, secondary periodicities were found: in the periods 1830–1900 and 1920–2010 an 11–15-year periodicity was observed, and from 1850 to 1880 a ~ 7-year periodicity. The longer historical data series (Figure 3B) consistently returns periodicities of 60 to 70 years (slightly weaker from 1500 to 1570) and 100 to 120 years (particularly strong from 1650 to 1950) in the wavelet analysis. One could interpret this as multiples of the 32–40 year periodicity seen in the observational data, which would imply it to be a property of the climatic system for at least the past 650 years. Wavelet analysis of sedimentary data (Figure 3C) also reveals periodicities of 30 to 33 and 60 to 75 years. Compared to observational data, the sedimentary data lacks information on smaller events that did not exceed bankfull levels to cause overbank sedimentation and flood record registration. Nevertheless, based exclusively on the occurrence of moderate to large events, the 30–33 year periodicity is still observed as a significant pulse during most of the last *c.* 450 years (significance levels are not reached between AD 1675 and 1740). Combined, the wavelet analysis results for the three series identify an important multi-decadal mode of variability for the Lower Rhine flooding regime. Some of the observed periodicities, however, fluctuate in strength over time (Figure 3), and might relate to internal variability of the larger climate system.

The emergent periodicities in peak flows imply that when flood frequency–magnitude rating curves for the Lower Rhine are based on relatively short series, these may be biased towards an arbitrary subset of climatic modes. The use of longer time series would therefore subdue the effects of multi-decadal variations. Alternatively, previous studies demonstrated that, if no longer series are available, non-stationarity behaviour can also be assessed in flood frequency analysis by filtering data according to the observed periodicities (Franks *et al.*, 2015) or by accepting and integrating the observed non-stationarity as a conditional behaviour of the system (Machado *et al.*, 2015).

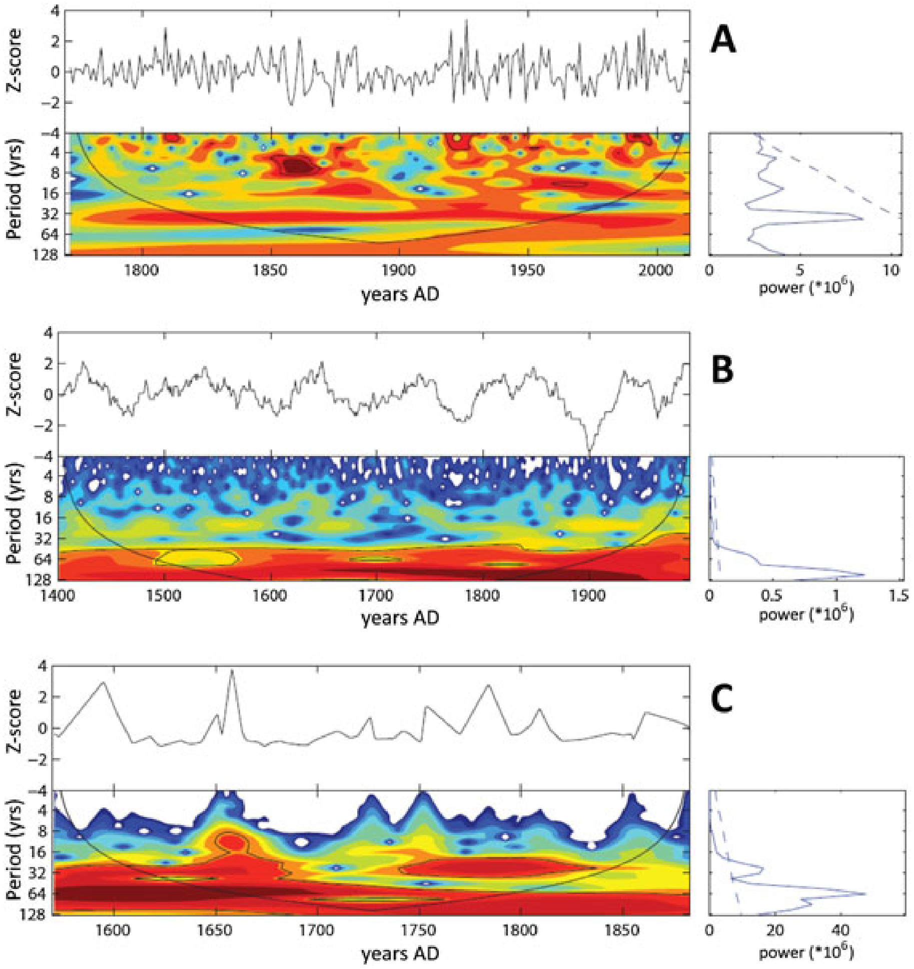

Figure 3. Wavelet spectra of Lower Rhine flooding, based on (A) annual peak discharge series, (B) historical flood damages, and (C) sedimentary flood units preserved in an abandoned channel. Blue and green colours indicate an absence or insignificant presence of periodicities of certain intervals over time, while red colours indicate a strong presence of such periodicities in the data series. The black line in the visual spectra and the dashed line in the power-plot (frames on the right, indicating the strength of a periodicity over a specific interval – plotted on same vertical time axis for periods as wavelet spectra) represent a 95% confidence level.

Climatic Variability and Lower Rhine Flood Risk

Potential underlying oscillatory climate controls for the observed variability in flood activity of the Lower Rhine are the AMO and NAO. The AMO is thought to be driven by fluctuations in the strength of the Atlantic Thermohaline Circulation (Kerr, 2005; Knight *et al.*, 2005; Dima and Lohmann, 2007), with a strong modulation of autumn and winter sea surface temperatures in the Arctic region (Chylek *et al.*, 2009). Correlations have been suggested between the AMO and floods in North America (Enfield *et al.*, 2001), Atlantic storm track configuration and intensity (Goldenberg *et al.*, 2001), and winter temperatures and glacier lengths in the Swiss-Alps (Huss *et al.*, 2010). Similar to the AMO, fluctuations in the NAO influence meteorological patterns and the configuration of storm tracks over Europe, and are thus likely to have an imprint on hydroclimatic records (Hurrell *et al.*, 2001).

Figure 4 shows that these drivers of the North-Atlantic climate show similar phasing as Lower Rhine historical flood series (e.g. Schlesinger and Ramankutty, 1994; Wanner *et al.*, 2001; Knudsen *et al.*, 2011). Especially a close visual resemblance between Lower Rhine flooding (31-year running mean flood intensity) and the AMO index (13-year smoothed curve shown in Knight *et al.*, 2005) seems to be present (Figure 4). Regression analysis reveals, however, a fairly moderate degree of correspondence ($r = 0.63$) between the Lower Rhine flood index and the 30-year smoothed AMO curve (derived from van Oldenborgh *et al.*, 2009), which may be caused by the use of simple linear regression methods to establish correlation coefficients, so phase shifts by lagged responses and non-linear relations were currently not assessed.

The flooding regime of the Lower Rhine also demonstrates similar phasing as the winter NAO; reconstructed back to the early sixteenth century based on temperature, pressure and precipitation records over Europe (Luterbacher *et al.*, 2001; Figure 4) and even further back using tree-ring and speleothem (bio)geological archives respectively from Morocco and Scotland (Trouet *et al.*, 2009). The Lower Rhine record correlates especially well with the Trouet *et al.*, (2009) winter NAO record ($r = 0.69$; excluding the period after 1825 because of a change to anticorrelation, see later) – to a somewhat lesser extent with the Luterbacher *et al.* (2001) record ($r = 0.46$; between 1658 and 1880 and $r = -0.52$ after 1880 when an anticorrelation exists), presumably because the latter is a compiled record from sites with a relatively large spatial distribution and positioned in multiple NAO-impact zones. In general, positive winter NAO phases align with increased flood frequency of the Lower Rhine, and the largest events of the last six centuries were all generated in NAO+ periods (Figure 4).

When the exact timing of the largest flood events is compared with general Lower Rhine flood activity, their timing and phasing does not always match (Table II; Figure 4A). While all extreme floods are positioned in NAO+ periods, some of the

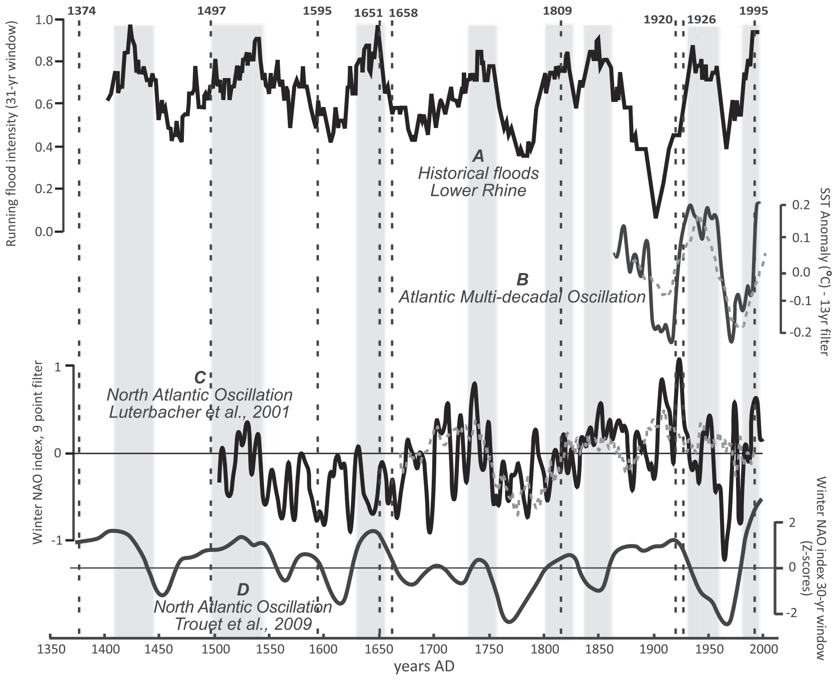

Figure 4. Comparison of trends in (A) Lower Rhine flooding based on a historical by-proxy flood series (explanation in Table I) derived from damage reports (phases of relatively high Lower Rhine flood activity are shaded grey in the background) and the timing of extreme events (dashed vertical lines; Toonen, 2015) with (B) the Atlantic Multi-decadal Oscillation [Knight *et al.* (2005) and 30-year smoothed curve based on data from van Oldenborgh *et al.* (2009)] and the North Atlantic Oscillation (C and D). Climate indices are presented in their original published form and in a 30-year smoothed curve (grey dashed lines) used for establishing correlations with Lower Rhine flooding.

largest events occurred in episodes of general low or moderate flood activity, whereas others are in phase with generally increased flood activity. These observations suggest that extreme events and general flooding are not always in a straightforward way connected – and potentially responsive to slightly different (unidentified) components of the Atlantic climate system. In a general sense, floods appear to be driven by NAO/AMO (hence the similarities shown in Figure 4), but specific meteorological conditions during each winter and early spring determine the actual generation of peak discharges. Basically, this means that high peak discharges can technically also be generated in episodes of generally reduced flooding, and vice versa, despite slightly less favourable general climate conditions for the generation of such events.

The period from 1825 to 1960 is rather anomalous, because it shows an anticorrelation between the winter NAO and flood activity in the Lower Rhine. This shift in NAO expression on Lower Rhine flooding might be explained by the complexity of the Rhine basin, with its tributaries located in upstream regions that respond differently to changes in NAO strength and mode. A possible explanation is that from 1825 to 1960, a different subset of tributary systems (compared to the 'usual-suspect' tributaries in the standard NAO+ mode) were the dominant source regions for generating peak flows. For the flood-rich period around 1845–1855, it is well-documented that in addition to the Moselle and Main Rivers (the main sources for recent floods in the NAO+ mode), also the Upper Rhine in Switzerland contributed significantly to downstream flooding (Wetter *et al.*, 2011). The flood-rich period between 1925 and 1955 is more difficult to explain, as over that period none of the large tributary catchments show clear evidence for an anomalous increase in peak flows. This hypothesis of changing contributions by individual tributary systems during a specific NAO-mode needs, however, further confirmation from historical records and requires testing of the effects of a changing storm track configuration on differential flood activity within the Rhine basin with numerical models.

Previous studies in the Rhine basin have found similar correlations between NAO and flood activity (e.g. Wirth *et al.*, 2013; Schulte *et al.*, 2015). These records correlate strongly with the summer NAO, affecting flood activity thus mainly during summer. Lower Rhine flooding rarely occurs during summer

Table II. Timing and flood generating mechanism of largest Lower Rhine floods (AD 1350–present).

Flood event (year AD)	Month	Main flood-generating factors (Krahe and Larina, 2010)	Years since previous major event (intermittency)	General mode of flood activity (Toonen, 2015)
1374	February	Rain and snow melt	32	moderate
1497	January	Rain and snow melt	132	moderate
1595	March–May	Rain and snow melt	98	low
1651	January	Rain and snow melt	56	high
1658	February–March	Snow melt	7	moderate
1809	January	Snow melt	151	high
1920	January	Rain fall	111	low
1926	January	Rain and snow melt	6	moderate
1995	January	Rain fall	69	high

(Toonen, 2015), which suggests that the summer NAO is of rather limited importance for downstream cumulative discharges. The spatial variability of NAO imprints, summer versus winter correlations and with increased flood activity during either positive or negative modes, is noted to differ among catchments in upland regions (Swierczynski *et al.*, 2013; Wirth *et al.*, 2013). Alpine sub-catchments thus not necessarily 'collaborate' to produce downstream Lower Rhine peak discharges with exception of early spring melt pulses that are induced by seasonal changes.

Understanding and assessing possible changes in the (future) occurrence of extremes in large river systems with a complex catchment configuration and different sub-catchment flood-generating factors and seasonality (Photiadou *et al.*, 2016), is not straightforward. The driving factors of large Lower Rhine floods have been heavy rainfall and snowmelt, and generally a combination of both (Table II). In a warming climate, extreme (stacked) snow accumulation over a large part of the Lower Rhine catchment is likely to become more rare (Kundzewicz *et al.*, 2006), as precipitation will predominantly fall as rain that is conveyed downstream directly. Intense rainfall over the Moselle and Main tributaries produced large floods in 1993 and 1995 without a significant contribution of snowmelt (Engel, 1997), but these were events with an associated recurrence time of less than a century (Toonen, 2015) and must be regarded as of a considerably smaller magnitude than for instance the 1374 flood (van Doornik, 2013). It is anticipated that climate change will enhance precipitation and precipitation intensity during winter, and rainfall-based events are expected to occur more frequently (Middelkoop *et al.*, 2001; IPCC, 2012; KNMI, 2014).

In addition to an anticipated systematic increase in general flood activity in a greenhouse climate, the AMO and NAO will also continue to be of importance as they may provide the instantaneous meteorological boundary conditions under which peak flows of the Lower Rhine arise. Based on its pacing, a reduced AMO strength was predicted for the first three decades of the twenty-first century (Kerr, 2005). Indeed, the Lower Rhine has experienced not a single event of discharge exceeding 10 000 $m^3 s^{-1}$ (recurrence time 10–20 years; Figure 2) in the past 20 years, rendering the present to a period of relatively reduced flood activity, despite transient effects of anthropogenic climate change and a postulated increase in the probabilities of hydrological extremes. Whether Lower Rhine flood magnitudes will increase after the present flood-poor interval will largely depend on upstream responses to intensification of rainfall versus stacked snow accumulation and their cumulative downstream effect on peak discharges, and importantly on catchment-wide flood mitigation which may either hamper (by buffering and retention) or promote (by increasing dyke height) downstream flood pulse propagation.

Conclusions

This paper demonstrates the existence of non-stationarity in the Lower Rhine flood regime over the past *c.* 650 years. Flood reconstructions of the past centuries yield a 30–40 and 60–75 year periodicity in flood occurrences. Similarities between fluctuations in past flood intensities and AMO and NAO strengths suggest that these North-Atlantic climate oscillations are important controls for the emergence of peak flows in the Lower Rhine. Remarkably, the highest reconstructed peak flows did not always occur during periods of generally increased flood activity. This indicates that specific meteorological conditions are an extra requirement for the generation of extreme peak discharges, on top of general climate conditions that set the overall probabilities for floods to occur.

Climatic non-stationarity considerably affects frequency–magnitude estimates when these are based on time series of observed discharges over short (up to a century) intervals. Flood frequency–magnitude estimates based on longer time series are less sensitive to multi-decadal periodicities, and could provide more robust estimates of peak flow probabilities. Further study of specific climatic drivers for periodicities in flood activity and the use of longer records (e.g. sedimentary flood archives), has the promise of revealing underlying controls for extreme flood occurrence. The compilation of observational, historical and sedimentary data, and magnitude estimates backed-up with hydraulic modelling provide independent checks on extreme flood magnitude predictions that are generated by statistical processing. Adopting a multi-disciplinary approach with full consideration of available records, analysis of non-stationarities and identification of its climatic drivers, and assessment of specific catchment responses to climate change is a major step forward in producing evidence-based flood risk assessments, both for the present and for future scenarios.

Acknowledgements—This paper was written as a contribution to the ESPL special issue 'Stormy Geomorphology', organized by Larissa Naylor (University of Glasgow). This research was supported by Deltares and a NWO Rubicon Fellowship grant to WHJ Toonen (825.14.005). The authors thank Timme Donders (Utrecht University) for supporting analysis of flood periodicities, and the reviewers for useful comments and support.

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