

RECONSTRUCTING PEAK DISCHARGES OF HISTORIC FLOODS OF THE RIVER AHR, GERMANY

THOMAS ROGGENKAMP and JÜRGEN HERGET

With 9 figures and 3 tables

Received 06. June 2013 · Accepted 13. March 2014

Summary: In the presented paper, peak discharges of historic floods in urbanized areas of different cities on the River Ahr in western Germany are reconstructed based on documentary sources from pre instrumental and the early instrumental period (1804–1937). Maximum water levels of five floods are denoted by flood-marks, with one of these events additionally documented by old photographs. The main challenge is the reconstruction of historic floodplain conditions and modifications influencing the cross-section area and the hydraulic roughness. In order to overcome this problem, a simple approach to estimate peak discharges of historic floods has been applied to the River Ahr. This approach includes a procedure for reconstructing the hydraulic parameters of the river channel and overflowed areas, coupled with an approach for the verification of estimated peak discharge reliability. Five reconstructed discharge maxima are presented. One of these events is well documented by numerous photographs, taken at different times of day, which allow the reconstruction of a hydrograph peak. The validation of the technique by comparison with recent gauged floods reveals results of adequate accuracy. The results show that reconstructed historic floods were partially larger than any gauged flood of the River Ahr.

Zusammenfassung: Der Artikel behandelt die Rekonstruktion von Scheitelabflüssen historischer Hochwasser in besiedelten Gebieten verschiedener Städte an der Ahr, basierend auf anthropogen erstellten Quellen aus der Zeit vor hydrologischen Messungen bis zur Zeit früher Messungen (1804–1937). Für fünf Hochwasserereignisse sind Höchstwasserstände in Form von Hochwassermarken überliefert. Eins dieser Hochwasser ist zusätzlich durch alte Fotoaufnahmen dokumentiert. Als hauptsächliche Herausforderung gilt die Rekonstruktion der Beschaffenheit sowie der Umwandlung der historischen Aue, welche sich auf das Querprofil und die hydraulische Rauigkeit auswirken. Um dieses Problem zu bewältigen, wurde ein simpler Ansatz zur Berechnung von Scheitelabflüssen historischer Hochwasser für die Ahr angewandt. Der Ansatz umfasst ein Verfahren zur Rekonstruktion hydraulischer Parameter im Flussbett sowie weiterer überspülter Bereiche und ist mit einem Plausibilitätstest der berechneten Scheitelabflüsse gekoppelt. Insgesamt werden fünf rekonstruierte Scheitelabflüsse präsentiert, wobei eines der rekonstruierten Hochwasser so umfangreich durch Fotomaterial, welches zu verschiedenen Zeiten im Verlauf des Ereignisses entstand, dokumentiert ist, dass die Rekonstruktion eines Teils der Hochwasserganglinie möglich ist. Die Plausibilitätsprüfung des Rekonstruktionsverfahrens durch Vergleiche zu rezent gemessenen Hochwassern zeigt, dass die Ergebnisse von hinreichender Genauigkeit sind. An den Ergebnissen ist abzulesen, dass die historischen Hochwasser von deutlich größerem Ausmaß waren, als sämtliche rezent gemessenen Hochwasser der Ahr.

Keywords: Historic flood, palaeohydrology, flood reconstruction, discharge estimation, River Ahr, Eifel

1 Introduction

Water level data for historic floods provide important information on potential magnitudes of contemporary floods. Furthermore, information on historic floods enables a comparison with recent floods to help classifying them. Historic flood levels can be found as markings on historic buildings, identifying the maximum flood level, or in documentary sources. Usually, written descriptions are qualitative, such as “in consequence of the Ahr-flood, great damage was affected everywhere...” (SEEL 1983). After careful interpretation and analysis, many can be used as a

flood level for historic times as is the case for rivers in Central Europe (KRAHE 1997; PFISTER 1999; WITTE et al. 1995; GLASER and STANGL 2004; SUDHAUS et al. 2008; MERZ et al. 2011; HERGET 2012) depending on the quality and quantity of the data. The approach of flood frequency analysis based on gauged flood events is well established, albeit it has to deal with the serious problem of statistical unsteadiness of datasets (e.g. SAVENIJE 1995; BENITO et al. 2004; KIDSON and RICHARDS 2005; MACDONALD 2013). By adding a significantly increased number of large flood events before the period of instrumental gauging, these datasets can be enhanced considerably (e.g. WITTE et

al. 1995; BENITO and THORNDYCRAFT 2005). Direct utilisation of these stage records in order to predict actual flood discharges is impossible due to frequent, mainly anthropogenic, modification of channels and nearby floodplains since historic times. For comparable discharges, the modern water levels would reach a different elevation, probably in most cases higher due to the decreased cross-section areas related to dykes, constructions and settlements on the floodplain. Therefore, the historic flood levels must first be transformed into historic peak discharges. These discharge values can then be used to estimate comparable modern-day flood levels by deriving peak discharges from historic events. In view of methodological problems, flood discharge estimations based on historic flood levels in urban areas are quite rare (e.g. BRÁZDIL et al. 1999; THORNDYCRAFT et al. 2003; MACDONALD et al. 2006; HERGET and MEURS 2010; WETTER et al. 2011; ELLEDER et al. 2013). In this case study, in addition to flood marks, historical photos are used. In comparison to flood marks, photos have the advantage of documenting a historic flood event in its development. Thus, the discharge can be quantified at different points in time. The consideration of how anthropogenic floodplain modifications impact upon the cross-section area and hydraulic roughness is one of the main challenges of palaeoflood research in such contexts. In order to overcome these problems, a simple approach to estimate the peak discharges has been developed and applied to the River Rhine at the city of Cologne (HERGET and MEURS 2010) as well as the River Vltava at Prague (ELLEDER et al. 2013). In this study, the approach is applied to a smaller river for the first time. In contrast to HERGET and MEURS (2010) and ELLEDER et al. (2013), peak discharges are quantified at several locations. One flood event was reconstructed at all locations, which helps to reconstruct the special variation of the flood wave. Multiple reconstructions of a single flood event allow a greater plausibility of results. This approach includes a procedure for reconstructing the hydraulic parameters of the river channel and inundated floodplain, as well as a final verification of the reliability of estimated peak discharges.

2 Historic flood levels at the Ahr from different documentary sources

The River Ahr, a tributary of the River Rhine, is located in western Germany. The catchment area of the river is 897.5 km² with its main tributary sources in the High Eifel Mountains. The current mean

discharge of the river at Altenahr, which is located 31.7 km upstream the confluence, is 6.95 m³ s⁻¹ with a peak monitored discharge of 214 m³ s⁻¹, recorded in 1993 (LANUV NRW 2011). The depth of flow in the river channel for mean discharge is 0.75 m above gauge zero point (160.51 m above sea level) and 3.49 m above gauge zero point during the highest gauged flood stage (LANUV NRW 2011). Most foundations of the towns in the area took place in medieval times. Flood descriptions have been handed down since AD 1348 and recorded flood levels date back to 1804.

Floods before 1804 are not quantitative documented so the period of interest for this study begins in 1804 and is terminated by the installation of the first discharge measuring gauge in 1937. Numerous floods are recorded in different archives for this period and compilations of this information are provided by, for example ULRICH (1938), FRICK (1955), SEEL (1983) and KOHL (2007) – for a complete list see ROGGENKAMP (2012). Flood level markings are located in three places, namely Ahrweiler, Dernau and Walporzheim in the lower parts of the river course (Fig. 1). Flood level markings in Dernau and Walporzheim were placed on houses, whereas markings in Ahrweiler were made in a bankside road tunnel. In addition, historic photographs, picturing a flood, which occurred in 1910, were taken in the city of Neuenahr (Fig. 2). In this study historic photographs can be useful, but must be chosen carefully, because of possible subsequent editing (Fig. 3). From these sources, five flood events were considered in this study (Tab. 1). By reason of diverse locations, parameters for the estimation of peak discharges must be determined for each of them. Due to clarity only the location of Bad Neuenahr is presented here (cf. ROGGENKAMP 2012 for further details).

3 Parameters for the estimation of peak discharges

Based on the empirical Manning equation for mean flow velocity (CHOW 1959), peak discharges for the selected historical flood events are estimated as

$$Q_p = A_p R_p^{2/3} S^{1/2} n^{-1}$$

With Q_p peak discharge, A_p cross-section area during the highest flood level, R_p hydraulic radius during the highest flood level, S slope and n hydraulic

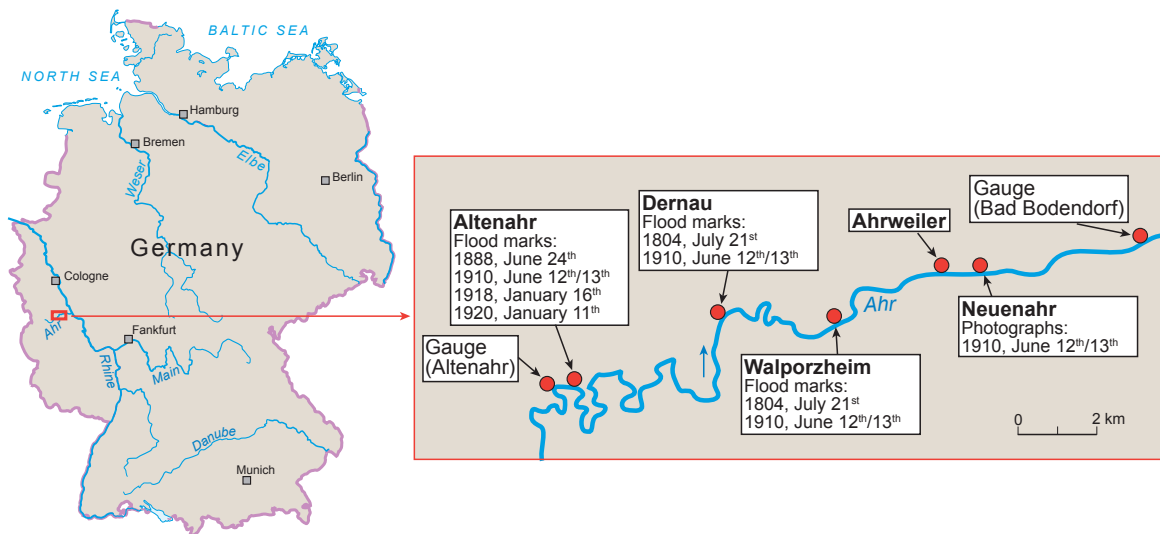


Fig. 1: Locations with historic sources of flood levels

lic roughness coefficient according to Manning. As will be explained in detail below, the peak discharge is calculated separately for five individual elements of the cross-section area A and subsequently summarized to a single value for each flood event.

3.1 Cross-section area A

The reconstruction of the inundated floodplain area is based on data from historic maps, photographs and engineering drawings of bridge constructions and cover the periods of with the floods listed in table 1. Based on these illustrations, any significant topographic changes – including land use change on the floodplain – can be traced back through time. A cross-section profile is reconstructed beginning in the city centre on the northern bank, across the floodplain area through the channel zone to the floodplain area on the southern bank (Fig. 4). The length of the profile is 185 m.

During the entire period of interest in this study, the principal form of the cross-section profile was not significantly modified. Comparing the city map from 1903 (Fig. 4) with current maps, it is obvious that the settlements did not occupy more extensive areas along the cross-section profile.

The relief data were derived from modern high-resolution topographic maps with scales of 1:5000, as well as geodetic surveys. Due to the small dimensions of the River Ahr, it never was used for navigation, as such bathymetric maps were not created. However the channel was canalized

and dredged before the flood of 1910 occurred in Neuenahr. Possible trends of incision or deposition of the channel bed can not be measured, so the recent channel topography is approved for the entire period of interest.



Fig. 2: Photograph picturing the flood-event from June 13th 1910, taken in Neuenahr



Fig. 3: Photograph supposed to picture the flood event from June 13th 1910. The water was edited later and the flood level was exaggerated

3.2 Hydraulic radius R

The hydraulic radius is calculated as $R=A/P$, with cross-section area (A) and wetted perimeter (P). Like the cross-section area, the wetted perimeter can be determined from modern topographic maps and from geodetic surveys considering the same properties of the features along the profile as discussed above.

3.3 Slope S

As in numerous previous palaeohydrological studies, the slope (S) is related to the slope of the water level instead of the slope of the energy line according to Manning equation (CHOW 1959). During and after the time of interest no significant changes influencing the slope of the river channel took place. The modern value of 0.0035 mm^{-1} is applied for the water levels in Neuenahr.

3.4 Manning's roughness coefficient n

Estimating the hydraulic roughness is the principal challenge in reconstructing flood discharges. Numerous factors influence the values, changing by place and time. All elements affecting the hydraulic roughness (CHOW 1959) are considered in the algebraic form of:

$$n = (n_1 + n_2 + n_3 + n_4 + n_5 + n_6 + n_7 + n_8 + n_9) m$$

With n_1 surface roughness, n_2 vegetation, n_3 channel irregularity, n_4 channel alignment, n_5 silt-ing and scouring, n_6 obstruction, n_7 variations of stage and discharge, n_8 sediment load (density of water), n_9 seasonal changes, and m as correction factor for meandering of the channel. Each of the five elements of the cross-section profile are described below in detail, an individual roughness coefficient n is estimated to take into account individual aspects of hydraulic roughness. Elements of uncertainty remain and to quantify these, a range for each factor in each cross-section element mentioned above is given as $n_{x \text{ min}} < n_x < n_{x \text{ max}}$ and a mean value $n_{x \text{ mean}}$ derived.

3.4.1 Neuenahr – settled area

The left river bank was settled and urbanized during the period of interest. The main streets along the cross-section, namely Poststraße and Telegrafstraße, run transverse to the direction of flow. The buildings act as barrier and also the photographs taken in these streets show people standing in almost still water (Fig. 2). The mean flow velocity in the city is therefore assumed to be practically zero. By algebraic expression, the value of obstruction roughness (n_6) equals infinity ($v = 0 \text{ ms}^{-1}$) due to the closed row of houses beginning orientated transverse to the flow direction. In practice this observation is an argument for leaving out this cross-section part in the estimation of peak discharges.

Tab. 1: Selected flood events between 1804 and 1937 along the River Ahr

| Year | Date | Cause of flood | Location | Water-level (a.s.l.) |
|------|--|----------------|--|---|
| 1804 | July 21 st | Rain | Dernau, Walporzheim | 125.12 m (Dernau) 111.77 m (Walporzheim) |
| 1888 | June 24 th | Rain | Altenahr | 162.64 m |
| 1910 | June 12 th to June 13 th | Rain | Altenahr, Dernau, Walporzheim, Neuenahr | 163.6 m (Altenahr) 123.6 m (Dernau) 110.31 m (Walporzheim) 93.3 m (Neuenahr) |
| 1918 | January 16 th | Snowmelt | Altenahr | 162.41 m |
| 1920 | January 11 th | Snowmelt | Altenahr | 162 m |

3.4.2 Neuenahr – non-built-up area

Between the built-up area and the northern river bank a small section of 9 m has no buildings. The area was predominantly overgrown with a slim grass strip, related to a surface roughness value of $0.012 < n_{1\text{mean}} < 0.018$ (ARCEMENT and SCHNEIDER 1989) with a mean value being $n_{1\text{mean}} = 0.015$. The vegetation has minor influence on roughness. Photographs show a small green

area with turf grass, related to a vegetation-value of $0.001 < n_{2\text{mean}} < 0.01$ (ARCEMENT and SCHNEIDER 1989) with $n_{2\text{mean}} = 0.005$. Given that winter flood events are not considered for the location of Neuenahr, it is not necessary to estimate the influence of winter vegetation. Within this part of the cross-section, some minor rises and dips have an effect on the degree of irregularity. These are quantified as $0.001 < n_{3\text{mean}} < 0.005$ (ARCEMENT and SCHNEIDER 1989) with $n_{3\text{mean}} = 0.003$.

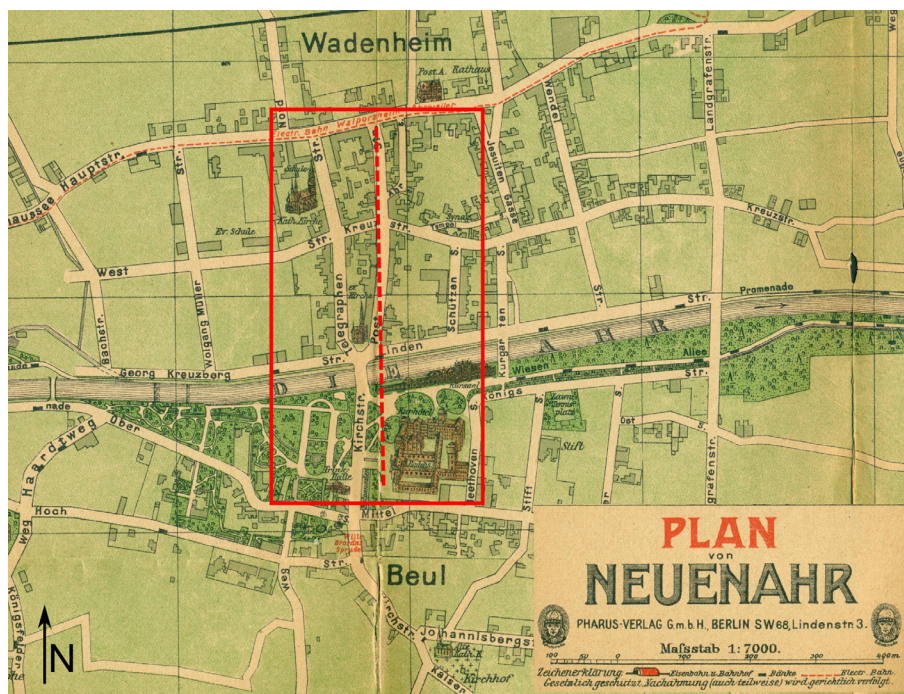


Fig. 4: Map of Neuenahr from 1903 with the location of the cross-section profile (KURDIREKTION BAD NEUENAH 1903)

Alignment effects (n_4) are not relevant, as the entire area is considered. Silting and scouring (n_5) is irrelevant by reason of an overgrown surface. Due to the minor influence of silting and scouring for the roughness coefficient these effects can be disregarded.

The degree of obstruction (n_6) has a minor effect on roughness, as obstacles are limited to lampposts. The estimated range is $0.003 < n_{6\text{mean}} < 0.005$ (ARCEMENT and SCHNEIDER 1989) with $n_{6\text{mean}} = 0.004$. Stage and discharge effects (n_7) and the sediment load (n_8) are not of further importance for this element of the cross-section profile. The sediment load (n_8) can not be quantified directly and, as a result, the generalizing empirical character of the Manning equation is assumed to be less important. For this observation area only one single historic flood, which occurred in summer, is reconstructed. As such seasonal changes (n_9) are not considered. In this area the River Ahr has a linear flow direction so that the correction factor for meandering (m) is not of importance.

3.4.3 Northern river bank

In the time of interest, a floodplain on both sides of the river existed. Different illustrations of the floodplain give information on the coverage of vegetation and condition (Fig. 5). The floodplain has a firm surface, related to a value of $0.025 < n_{1\text{mean}} < 0.032$ (ARCEMENT and SCHNEIDER 1989) with $n_{1\text{mean}} = 0.028$. The floodplain area is mostly woodless with grass coverage added by smaller weeds. The related vegetation-value is quantified as $0.01 < n_{2\text{mean}} < 0.025$ (ARCEMENT and SCHNEIDER 1989) with $n_{2\text{mean}} = 0.018$. Within the floodplain some moderate rises and dips have an effect on the degree of irregularity, quantified as $0.006 < n_{3\text{mean}} < 0.01$ (ARCEMENT and SCHNEIDER 1989) with $n_{3\text{mean}} = 0.008$. As mentioned above, alignment effects (n_4) as well as silting and scouring (n_5) can be disregarded. The different illustrations show merely smaller obstacles with minor effects on roughness coefficient, related to a value $0.001 < n_{6\text{mean}} < 0.004$ (ARCEMENT and SCHNEIDER 1989) with $n_{6\text{mean}} = 0.002$. For the floodplain area the effects of stage and discharge (n_7), sediment load (n_8) and seasonal changes (n_9) are not of further importance. As mentioned above, the effect of meandering (m) is also not considered.



Fig. 5: Photograph of the northern river bank in 1909

3.4.4 River channel

Recent investigations reveal that the channel bottom of the River Ahr in Neuenahr consists of medium to coarse gravel with few boulders and has moderate to serve irregularities. According to CHOW (1959), this can be transferred to a surface roughness factor of $0.026 < n_{1\text{mean}} < 0.03$ with $n_{1\text{mean}} = 0.028$ and a channel irregularity of $0.01 < n_{3\text{mean}} < 0.02$ with $n_{3\text{mean}} = 0.015$. The vegetation in channel bed is nearly negligible in the range $0 < n_{2\text{mean}} < 0.005$ (CHOW 1959) with $n_{2\text{mean}} = 0.002$. As all other factors are negligible for large magnitude flood events, the hydraulic roughness of the channel is in the range $0.038 < n_{\text{mean}} < 0.053$ with the mean value of $n_{\text{mean}} = 0.045$.

The river has no significant curvature indicating that channel alignment (n_4) is not an influence. According to scale and surface, silting and scouring (n_5) are of minor importance. Upstream from the cross-section the Kurgarten-Bridge was present in 1910. Historic photographs document that the bridge did not have bridge piers that could influence the roughness coefficient, therefore the effect of obstruction (n_6) does not have to be considered further. Stage and discharge effects (n_7) are considered to be unimportant due to the separation of the cross-section area into different elements which are studied individually. The sediment load (n_8) can not be quantified directly and, as mentioned above is assumed to be less important. As previously mentioned, the effect of seasonal changes (n_9) is not relevant in this case. The channel of the river is practically straight within the limits of the city, so the correction factor for channel meandering is assumed to be $m=1$.

3.4.5 Southern river bank and floodplain

The condition of the southern bank and floodplain differs slightly from the northern river bank in reference to increased obstacles (n_6) and vegetation coverage (n_2). The southern floodplain ranges to a former recreation area, a part of the health resort Neuenahr. Different illustrations show flowerbeds, hedges, bushes and isolated trees. The vegetation has a major effect on the roughness and is quantified as $0.02 < n_{2,mean} < 0.03$ (ARCEMENT and SCHNEIDER 1989) with $n_{2,mean} = 0.025$. In addition, illustrations show street furniture occurring as obstacles and affecting the roughness, related to a value $0.015 < n_{6,mean} < 0.02$ (ARCEMENT and SCHNEIDER 1989) with $n_{6,mean} = 0.018$. Other parameters affecting the roughness do not differ from the northern river bank and are quantified similarly.

4 Results and reliability check

Based on the data and derived parameters, peak discharge for the listed (Tab. 1) historic large-scale flood events were estimated (Fig. 6). The principle of the approach is illustrated by the flood event of 1910 (Tab. 2). Details for the other flood events, particularly the flood event of 1804, which was the major flood event on the River Ahr in historic times, are given by ROGGENKAMP (2012). Estimated discharges for all reconstructed floods are listed in table 3. The flood event of 1910 presented a consid-

erable danger for residents. Several structures near the River Ahr were damaged and wooden building materials mobilized, becoming a danger for bridge constructions along the stream (ULRICH 1938). For mean roughness values, the peak discharge can be estimated as about $590 \text{ m}^3 \text{ s}^{-1}$, with a range of $470 \text{ m}^3 \text{ s}^{-1} < Q_{peak} < 750 \text{ m}^3 \text{ s}^{-1}$ considering maximum and minimum roughness coefficients. Note that about 69% of the discharge flowed within the channel zone.

As mentioned above, the flood event of 1910 is well documented by numerous photographs, taken in Neuenahr. Picturing the accurate water level, the presented approach affords the calculation of relative discharges. Some of these photographs show, apart from the water level, a clock (Fig. 7). This fortunate circumstance allows a connection between time and relative level, based on photographs, to estimate a hydrograph peak of a historic flood (Fig. 8).

As several approximations are required to estimate the peak discharges of historic floods, peak discharges of modern gauged flood events have been calculated applying the same approach. For illustration, the two flood events from May 30th 1984 and March 16th 1988 have been selected. Both flood events had water levels with heights, sufficient to reach a bankside road tunnel, mentioned above. Pictures showing the water levels inside the road tunnel were used as source for estimating the peak discharges. The resulting calculated peak discharges are $182 \text{ m}^3 \text{ s}^{-1}$ (1984) with range from 148 to $232 \text{ m}^3 \text{ s}^{-1}$, dependent on n -value and $176 \text{ m}^3 \text{ s}^{-1}$ (1988)

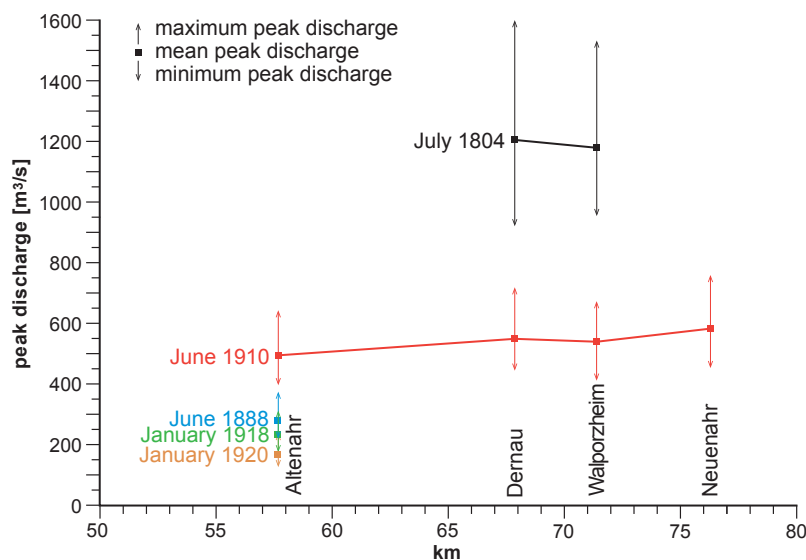


Fig. 6: Estimated peak discharges and critical range of historic floods at different locations

Tab. 2: Estimated parameters of the 1910 flood in Bad Neuenahr

| | Non-built-up area | Northern river bank | River channel | Southern river bank and floodplain | Entire relevant cross-section |
|--|-----------------------------------|-----------------------------------|------------------------------------|--|--------------------------------------|
| A cross-section area | 8 m ² | 36 m ² | 99 m ² | 68 m ² | 211 m ² |
| v mean flow velocity (for n_{mean}) | 1.87 m s ⁻¹ | 2.49 m s ⁻¹ | 4.09 m s ⁻¹ | 1.12 m s ⁻¹ | |
| Q_{mean} peak discharge | 15 m ³ s ⁻¹ | 90 m ³ s ⁻¹ | 405 m ³ s ⁻¹ | 76 m ³ s ⁻¹ | ~ 590 m ³ s ⁻¹ |

with range from 143 to 225 m³ s⁻¹. Comparing the discharges with the gauged peak discharges of 192 m³ s⁻¹ (1984) and 190 m³ s⁻¹ (1988) the approach presented in this study underestimates observed values by an acceptable degree of error of 5 to 7%.

5 Discussion

The presented attempt to improve the estimation of peak discharges for the River Ahr based on a combination of knowledge of histori-

cal flood peak water levels, analysis of historic floodplain conditions and hydraulic calculation, has remained unequalled so far. Although ULRICH (1938) gives information on discharge of the flood event of 1910, these data refers to assumptions. In contrast to ULRICH (1938), the presented approach provides the first quantitative information on non-gauged floods of the River Ahr.

Estimated discharges within the floodplain represent about 30–65% of the total estimated discharge. Possible errors in the reconstruction of floodplain conditions may have major effect

Tab. 3: Discharge-reconstruction with range between maximum, mean and minimum discharge, dependent on n-value

| Location | Discharge | 1804 | 1888 | 1910 | 1918 | 1920 | Gauged data |
|----------------------|-------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|------------------------------|
| Altenahr | Q _{max} | – | 360 m ³ /s | 630 m ³ /s | 300 m ³ /s | 220 m ³ /s | HHQ = 214 m ³ /s |
| | Q _{mean} | – | 280 m ³ /s | 500 m ³ /s | 240 m ³ /s | 170 m ³ /s | MHQ = 90.6 m ³ /s |
| | Q _{min} | – | 230 m ³ /s | 410 m ³ /s | 190 m ³ /s | 140 m ³ /s | MQ = 6.95 m ³ /s |
| Dernau | Q _{max} | 1600 m ³ /s | – | 710 m ³ /s | – | – | – |
| | Q _{mean} | 1210 m ³ /s | – | 550 m ³ /s | – | – | – |
| | Q _{min} | 940 m ³ /s | – | 460 m ³ /s | – | – | – |
| Walporzheim | Q _{max} | 1520 m ³ /s | – | 660 m ³ /s | – | – | – |
| | Q _{mean} | 1180 m ³ /s | – | 540 m ³ /s | – | – | – |
| | Q _{min} | 970 m ³ /s | – | 430 m ³ /s | – | – | – |
| Neuenahr | Q _{max} | – | – | 750 m ³ /s | – | – | – |
| | Q _{mean} | – | – | 590 m ³ /s | – | – | – |
| | Q _{min} | – | – | 470 m ³ /s | – | – | – |
| Bad Bodendorf | Q _{max} | – | – | – | – | – | HHQ = 214 m ³ /s |
| | Q _{mean} | – | – | – | – | – | MHQ = 85.5 m ³ /s |
| | Q _{min} | – | – | – | – | – | MQ = 6.31 m ³ /s |



Fig. 7: Photographs documenting the water level of the flood event of 1910 in Neuenahr during June 13th

on total discharge, but due to exactness of used sources, the potential for error should be low. If flood inventories and information on the development of the floodplain area since historic times are available, the presented method can be applied in numerous other areas in Europe (BENITO 2003). BRÁZDIL et al. (1999) and GLASER (2008) research on historic floods in Europe, without quantifying peak discharges. The approach, applied in this study, was also applied by HERGET and MEURS (2010) and ELLEDER et al. (2013) who reconstructed accurate peak discharges of historic floods. Also in other areas like China (CHENG-ZHENG 1987) or India (KALE 1998) historical floods are quantified, but due to lacking historical sources, the reconstructed peak discharges are arguable. Like the established slack-water-deposit approach (BAKER et al. 1983) frequently applied outside settled areas, the estimated peak discharge provides a valuable contribution for flood frequency analysis beyond just the timing of the event. The presented approach can not help to extend the series of measurement of recent floods. Due to the fact, that only single events are reconstructed, the series is incomplete with no statistical validity. KIRBY et al. (1987), HOUSE et al. (2002), BENITO et al. (2004) and BENITO and THORNDYCRAFT (2005) discuss the problem in adding single floods from historic times to the gauged datasets in detail.

The results reveal that four out of five reconstructed historic flood events of the River Ahr were larger than any recently gauged floods. Particularly with regard to the high-magnitude flood events of 1804 and 1910 the recent danger of flooding is underrated in case of disregarding historic floods. The large discrepancy between recent mean discharge ($6.95 \text{ m}^3/\text{s}$) and reconstructed

peak discharges is conspicuous. The flood event of 1804 multiplies the mean discharge by about 170. Such differences occur only in smaller rivers such as River Ahr. The floods of 1804 and 1910 were both caused by persistent rainfall, especially in the southern catchment area (ULRICH 1938; FRICK 1955; PFISTER 1999; WEIKINN 2002). The flood event of 1910 was reconstructed at four locations. Results show no outlier, however, a trend is in evidence (Fig. 6). The peak discharge increases downstream slightly, due to persistent rainfall. Favourable state of sources allows not only the reconstruction of peak discharges but also of partial hydrograph of the flood event of 1910 in Neuenahr. The timed exactness is unprecedented so far and underlines the value of photographs for the quantitative reconstruction of historical floods.

As the reliability check indicates, the approach underestimates the factual peak discharge by 5 to 7%. The approach seems to be conservative and previous applications show a similar underestimation (HERGET and MEURS 2010; ELLEDER et al 2013).

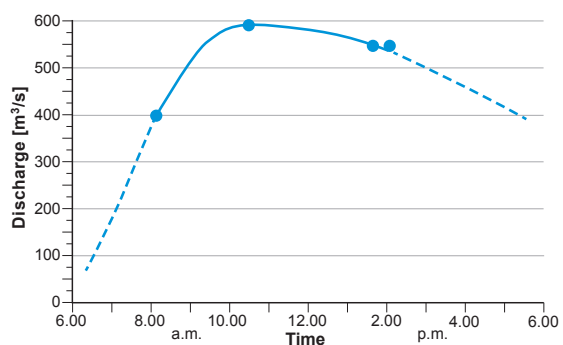


Fig. 8: Reconstructed hydrograph peak of the 1910-flood event in Neuenahr

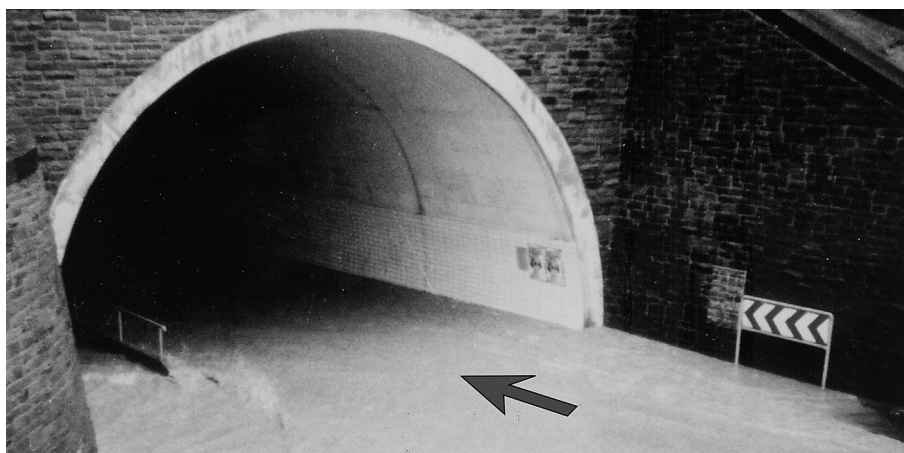


Fig. 9: Photography documenting the water level of the flood event of May 30th 1984 in Altenahr

6 Conclusion

The results for the River Ahr show that the approach to the peak discharge estimation of historic flood levels in a settled area presented in this paper can successfully be applied. The validation of the technique by comparison with recent gauged floods reveals results of sufficient accuracy. In addition to that, the high level of information contained within the sources allows the estimation of a hydrograph curve for the flood event from 1910 in Neuenahr. The results show that the flood from 1804 was the largest flood event on the River Ahr in historic times. The particularly high runoff values of the flood events of 1804 and 1910 are confirmed by written reports, which tell of devastating damages (ULRICH 1938; FRICK 1955; SEEL 1983; KOHL 2007).

A future challenge is to investigate the likely modern level of an event such as 1804 or 1910 in the settled areas along the River Ahr. Urban expansions reduced retention areas and the peak levels of historic flood events would, most likely, be higher with the current structure.

Acknowledgements

We appreciate the valuable support of L. Janta (district archive Ahrweiler) and S. Schütze (city archive Bad Neuenahr / Ahrweiler) who supplied many unpublished historic photographs, maps and bridge construction plans. Two anonymous reviewers supported the improvement of previous version of the manuscript.

References

- ARCEMENT, G. J. and SCHNEIDER, V. R. (1989): Guide for selecting Manning's roughness coefficient for natural channels and floodplains. Washington.
- BAKER, V. R.; KOCHER, R. C.; PATTON, P. C. and PICKUP, G. (1983): Paleohydrologic analysis of Holocene flood slack-water sediments. In: COLLINSON, J. and LEWIN, J. (eds.): Modern and ancient fluvial systems. Boston, 229–239. DOI: [10.1002/9781444303773.ch18](https://doi.org/10.1002/9781444303773.ch18)
- BENITO, G. (2003): Palaeoflood hydrology in Europe. In: THORNDY CRAFT, V. R.; BENITO, G.; LLASAT, M.-C. and BARRIENDOS, M. (eds.): Palaeofloods, historical data and climatic variability – applications in flood risk assessment. CSIC Consejo Superior de Investigaciones Científicas. Madrid, 19–24.
- BENITO, G. and THORNDY CRAFT, V. (2005): Palaeoflood hydrology and its role in applied hydrological sciences. In: Journal of Hydrology 313, 3–15. DOI: [10.1016/j.jhydrol.2005.02.002](https://doi.org/10.1016/j.jhydrol.2005.02.002)
- BENITO, G.; LANG, M.; BARRIENDOS, M.; LLASAT, M.-C.; FRANCES, F.; OUARDA, T.; THORNDY CRAFT, V.; ENZEL, Y.; BÁRDOSSY, A.; COEUR, D. and BOBEE, B. (2004): Use of systematic, palaeoflood and historical data for the improvement of flood risk estimation. In: Natural Hazards 31, 623–643. DOI: [10.1023/B:NHAZ.0000024895.48463.eb](https://doi.org/10.1023/B:NHAZ.0000024895.48463.eb)
- BRÁZDIL, R.; GLASER, R.; PFISTER, C.; DOBROVOLNÝ, P.; ANTOINE, J.-M.; BARRIENDOS, M.; CAMUFFO, D.; DEUTSCH, M.; ENZI, S.; GUIDOBONI, E.; KOTYZA, O. and SANCHEZ-RODRIGO, F. (1999): Flood events of selected European rivers in the sixteenth century. In: Climate Change 43, 239–285. DOI: [10.1023/A:1005550401857](https://doi.org/10.1023/A:1005550401857)
- CHENG-ZHENG, L. (1987): Investigation and regionalization of historical floods in China. In: Journal of Hydrology 96, 41–51. DOI: [10.1016/0022-1694\(87\)90142-9](https://doi.org/10.1016/0022-1694(87)90142-9)

- CHOW, V. T. (1959): Open-channel hydraulics. New York.
- ELLEDER, L.; HERGET, J.; ROGGENKAMP, T. and NIESSEN, A. (2013): Historic floods in the city of Prague – a reconstruction of peak discharges for 1481–1825 based on documentary sources. In: *Hydrology Research* 44, 202–214. DOI: [10.2166/nh.2012.161](https://doi.org/10.2166/nh.2012.161)
- FRICK, H. (1955): Das Hochwasser von 1804. In: *Heimatjahrbuch des Kreises Ahrweiler* 12, 43–51.
- GLASER, R. and STANGL, H. (2004): Climate and floods in Central Europe since AD 1000: data, methods, results and consequences. In: *Surveys in Geophysics* 25 (5–6), 485–510. DOI: [10.1007/s10712-004-6201-y](https://doi.org/10.1007/s10712-004-6201-y)
- GLASER, R. (2008): *Klimageschichte Mitteleuropas – 1200 Jahre Wetter, Klima, Katastrophen*. Darmstadt.
- HERGET, J. (2012) *Am Anfang war die Sintflut. Hochwasserkatastrophen in der Geschichte*. Darmstadt.
- HERGET, J. and MEURS, H. (2010): Reconstructing peak discharges for historic flood levels in the city of Cologne, Germany. In: *Global and Planetary Change* 70, 108–116. DOI: [10.1016/j.gloplacha.2009.11.011](https://doi.org/10.1016/j.gloplacha.2009.11.011)
- HOUSE, P. K.; WEBB, R. H.; BAKER, V. R. and LEVISH, D. R. (eds.) (2002): *Ancient floods, modern hazards – principles and applications of paleoflood hydrology*. Washington.
- KALE, V. S. (1998): Monsoon floods in India – a hydrogeomorphic perspective. In: *Geological Society of India Memoir* 41, 229–256.
- KIDSON, R. and RICHARDS, K. S. (2005): Flood frequency analysis – assumptions and alternatives. In: *Progress in Physical Geography* 29 (3), 392–410. DOI: [10.1191/0309133305pp454ra](https://doi.org/10.1191/0309133305pp454ra)
- KIRBY, W. H.; HUA, S.-Q. and BEARD, L. R. (eds.) (1987): Analysis of extraordinary flood events. In: *Journal of Hydrology* 96, 3–383.
- KOHL, M. (2007): Ahrhochwasser 1804. In: *Heimatjahrbuch des Kreises Ahrweiler* 64, 161–164.
- KRAHE, P. (1997): Hochwasser und Klimafluktuation am Rhein seit dem Mittelalter. In: IMMENDORF, R. (ed.): *Hochwasser – Natur im Überfluss?* Heidelberg, 57–82.
- KURDIREKTION BAD NEUENAHN (ed.) (1903): *Festschrift gewidmet den Teilnehmern der III. ärztlichen Studienreise in Bade- und Kurorte. Neuenahr*.
- LANUV NRW (ed.) (2011): *Deutsches Gewässerkundliches Jahrbuch Rheingebiet III 2007*. Essen.
- MACDONALD, N. (2013): Reassessing flood frequency for the River Trent, Central England, since AD 1320. In: *Hydrology Research* 44 (2), 215–233. DOI: [10.2166/nh.2012.188](https://doi.org/10.2166/nh.2012.188)
- MACDONALD, N.; WERRITTY, A.; BLACK, A. R. and MCEWEN, L. J. (2006): Historical and pooled flood frequency analysis for the River Tay at Perth, Scotland. In: *Area* 38 (1), 34–46. DOI: [10.1111/j.1475-4762.2006.00673.x](https://doi.org/10.1111/j.1475-4762.2006.00673.x)
- MERZ, B.; BITTNER, R.; GRÜNEWALD, U. and PIROTH, K. (eds.) (2011): *Management von Hochwasserrisiken*. Stuttgart.
- PFISTER, C. (1999): *Wetternachhersage – 500 Jahre Klimavariationen und Naturkatastrophen*, Bern.
- ROGGENKAMP, T. (2012): *Rekonstruktion historischer Hochwasser der Ahr*. Unpubl. Diploma thesis. Bonn.
- SAVENIJE, H. G. G. (1995): Recent extreme floods in Europe and the USA – challenges for the future. In: *Physics and Chemistry of the Earth* 20 (5–6), 433–437. DOI: [10.1016/S0079-1946\(96\)00001-8](https://doi.org/10.1016/S0079-1946(96)00001-8)
- SEEL, K. A. (1983): Die Ahr und ihre Hochwässer in alten Quellen. In: *Heimatjahrbuch des Kreises Ahrweiler* 40, 91–102.
- SUDHAUS, D.; BÜRGER, K.; DOSTAL, P.; IMBERY, F.; SEIDEL, J.; KONOLD, W.; MAYER, H. and GLASER, R. (2008): Rekonstruktion historischer Hochwasserabflüsse anhand meteorologischer und hydrologischer Daten. In: *Hydrologie und Wasserbewirtschaftung* 52 (4), 198–202.
- THORNDYCRRAFT, V. R.; BENITO, G.; LLASAT, M.-C. and BARRIENDOS, M. (eds.) (2003): *Palaeofloods, historical data and climatic variability – applications in flood risk assessment*. CSIC Consejo Superior de Investigaciones Cientificas. Madrid.
- ULRICH, C. (1938): Hochwasserkatastrophe der Ahr am 12./13. Juni 1910. In: *Jahrbuch des Kreises Ahrweiler* 6, 92–106.
- WEIKINN, C. (2002): *Quellentexte zur Witterungsgeschichte Europas von der Zeitenwende bis zum Jahr 1850. Hydrographie Teil 6 (1801–1850)*. In: BÖRNGEN, M. and TETZLAFF, G. (eds.): *Quellensammlung zur Hydrographie und Meteorologie*. Berlin.
- WETTER, O.; PFISTER, C.; WEINGARTNER, R.; LUTERBACHER, J.; REIST, T. and TRÖSCH, J. (2011): The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence. In: *Hydrological Sciences Journal* 56, 733–758. DOI: [10.1080/02626667.2011.583613](https://doi.org/10.1080/02626667.2011.583613)
- WITTE, W.; KRAHE, P. and LIEBSCHER, H.-J. (1995): *Rekonstruktion der Witterungsverhältnisse im Mittelrheingebiet von 1000 n. Chr. bis heute anhand historischer hydrologischer Ereignisse*. Lelystad.

Authors

Thomas Roggenkamp
 Prof. Dr. Jürgen Herget
 University of Bonn
 Department for Geography
 Meckenheimer Allee 166
 53115 Bonn
 Germany
 troggen@uni-bonn.de
 herget@giub.uni-bonn.de