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Discharges of past flood events based on historical river profiles

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Abstract

This paper presents a case study to estimate peak discharges of extreme flood events of Neckar River in south-western Germany during the 19th century. It was carried out within the BMBF research project RIMAX (Risk Management of Extreme Flood Events). The discharge estimations were made for the flood events of 1824 and 1882 based on historical cross profiles. The 1-D model Hydrologic Engineering Centers River Analysis System (HEC-RAS) was applied with different roughness coefficients. The results are compared (i) with contemporary historical calculations and (ii) in the case of a flood event in 1824 with the discharge simulation by the water balance model LARSIM (Large Area Runoff Simulation Model). These calculations are matched by the HEC-RAS simulation based on the standard roughness coefficients.

1 Introduction

The reconstruction of historical flood events represents an important subject for modern flood risk management. The estimation of discharges for historical extreme flood events extents existing discharge data series and improves statistical calculations, e.g. for the determination of return periods as well as for a better assessment of extreme flood events. The identification and quantification of historical flood events will also provide answers to the question whether frequency and magnitude of floods have increased during the past few centuries. For a well-founded flood-frequency analysis, the magnitude of the peak discharge of historical floods must be quantified (Cook, 1987). Therefore, the inclusion of historical data considerably improves the reliability of calculations of return periods for extreme flood events (IKSE, 2004; Payrastre et al., 2005).

Major damaging floods in Europe (e.g. Oder, 1997; Elbe, 2002 and 2006; Danube, 2006) resulted in a general interest in increasing flood risk and flood risk management. As a result of regional climate change the intensity of rainfall is likely to rise in Central Europe. Therefore, the flood risk is expected to increase in the future for specific regions like Northern, Central and Eastern Europe (KLIWA, 2003; IPCC, 2007). Additionally, the number of people and economic assets located in flood endangered areas is expected to increase further, resulting in a higher damage potential. Flood risk mapping can reduce potential economic and health damages and raise the risk awareness in the general population. For planners and engineers, extreme flood events are of high interest, although they are very rare in observational records (Enzel et al., 1993).

The knowledge of peak discharges represents the basis for flood area mapping. Flood level marks alone give insufficient information about the severity of a flood since hydraulic engineering may have influenced the stage-discharge relation over the course of time. Historical calculations of the discharge often appear not to be reliable (Pohl, 2007). In historical times as well as today, the data for the largest floods have frequently been indirect post-flood estimations. This is due to the fact that conventional stream gauge stations have great difficulties to record extreme floods accurately, since they may be inundated, damaged or destroyed (Benito et al., 2006).

Discharge measurements during flood conditions are very important, but were explicitly difficult to determine in historical times. Between 1867 and 1897, the effort to improve discharge measurements was increased, e.g. for the development of open channel flow resistance equations (Hager, 1994). Many of the historical discharge calculations cited in this paper originate from this time. Therefore, the informational value of these historical data must be examined before they can be used for statistical calculations, e.g. return times.

Bürger et al. (2006) calculated the discharge of the Neckar River for the 1824 extreme flood event using historical meteorological measurements and the water balance model LARSIM (Ludwig and Bremicker, 2006). Kidson et al. (2002), Barriendos and Coeur (2004), Thorndycraft et al. (2005) and Thorndycraft et al. (2006) used historical flood marks and recent cross sections of bedrock channels for the estimation of palaeodischarges.

In the presented study the discharge reconstruction for extreme floods on the Neckar and tributaries during the 19th century is tested using historical cross profiles. Furthermore, these results were compared to historical discharge calculations and simulations with the LARSIM model (Bürger et al., 2006).

2 Study area

The Neckar River with a catchment area of 14 000 km^2 is located in the south-western part of Germany and is a tributary of the Upper Rhine (Fig. 1). The Neckar has a length of 367 km and originates in the Eastern Black Forest at an elevation of 706 m a.s.l. The river passes through the cities of Tübingen, Stuttgart, Heilbronn, Heidelberg and Mannheim, where it discharges into the Rhine. Its main tributaries are the rivers Fils, Rems, Enz, Kocher and Jagst. The Neckar is also the river with the largest catchment area in the federal state of Baden-Württemberg (south-western Germany). Today, 202.5 km of the Neckar are navigable between Plochingen and Mannheim at the river mouth. Together with Rhine and Main rivers, the Neckar is one of the three main waterways in Baden-Württemberg.

During the 19th century, the area of the Neckar catchment was divided between five territorial states: The Grand Duchy of Baden, the Kingdom of Württemberg, the Prussian Province of Hohenzollern, the Grand Duchy of Hesse and the Kingdom of Bavaria (Fig. 2). The latter three only held minor percentages of the catchment area and the main channel of the Neckar River was situated in the former Grand Duchy of Baden and the former Kingdom of Württemberg. Therefore, most hydraulic engineering measures were primarily carried out and documented by these two states.

The first gauging station at the Neckar River was installed in Heilbronn in 1827 (Centralbureau für Meteorologie und Hydrographie, 1889). Continuous and systematic measurements of the water levels at six gauging stations were carried out from 1881 onwards (Statistisch-Topographisches Bureau, 1883). At present 17 gauging stations are installed along the Neckar. In the lower course of the Neckar River between Heidelberg and Mannheim, the mean, minimum and the mean flood discharges are 145 $m^3 s^{-1}$, 42 $m^3 s^{-1}$ and 1150 $m^3 s^{-1}$, respectively (LfU, 2005).

3 Material and methods

Different sources such as archive records and administrative reports from 19th century authorities where examined for suitable river cross profiles (Table 1). A number of cross profiles with various hydrological parameters were generated during the 19th century through the course of hydro-engineering measures to achieve better navigability and technical flood risk management along the Neckar River system. All historical profiles chosen for the discharge calculations in this study met the following criteria:

- information about the water level,
- specification of the elevation (water level and/or river bed),
- channel slope in the river section,
- water levels must not exceed the cross profile,
- no bridges and/or weirs to avoid backwater effects.

For the flood events of 1824 and 1882, discharges were calculated using eight and nine river cross profiles, respectively, along the Neckar River (Fig. 2 and Table 1). In the case of the 1824 flood event, the profiles used to calculate the discharges are situated between Plochingen (historical river km 212) and Obrigheim (river km 82). The last major inflows are the rivers Kocher and Jagst at river km 100. Therefore, the cross profiles at Obrigheim are representative for the lower course of the Neckar. For the Stuttgart section of the Neckar River, three suitable and exceptionally detailed cross profiles (profiles A5–A7 in Table 1 and Fig. 2) could be identified based on a historical record found in the City Archive of Stuttgart (1877).

The cross profiles for the 1882 flood event are located between Rottweil (river km 344) and Gemmrigheim (river km 137). In this case, there is no information available about discharges in the lower course of the Neckar after the inflow of the rivers Kocher and Jagst. At two profiles (Münster and Gemmrigheim, Table 1) there are water stages for both floods.

The selected cross profiles were digitized and the distances were converted from historical to SI-units. The discharge calculations were carried out using the 1-D hydraulic model HEC-RAS 3.1.3 (Hydrologic Engineering Center, 2005). Previously, this model has been used successfully for palaeoflood studies (O'Conner and Webb, 1987; Kidson et al., 2002; Benito et al., 2004; Thorndycraft et al., 2006). For the calculation of discharges, the single cross profiles were regionalized and the particular river slope was derived from the historical longitudinal profile of the Neckar River.

The most uncertain variable is the roughness coefficient (Manning's n; Cook, 1987). For example, a 50% error in the roughness coefficient results in a maximum error of 25% in the upper end of the rating curve (Sauer et al., 1984). For a difference of 50% in the roughness coefficient, Kidson et al. (2002) calculated a discharge error of 40% for a palaeoflood in a bedrock river. The channel conditions during floods (scour, fill, debris), however, are not known (Cook, 1987). For the adjacent flood plain, the uncertainty factor is higher due to changes in the vegetation cover. Especially for such flood plains where the historical land use is not known, this could have a significant effect. Therefore, a range of roughness coefficients (Manning's n) was used in this study, obtained by default values (Table 2). For the river bed, a standard value of 0.03 was used, which corresponds to the roughness coefficient found in historical hydraulic engineering documents. For flooded areas outside the river bed, where no land use information and roughness coefficients were available, a high grass cover vegetation or the upper limit of short grass cover with a roughness coefficient of 0.035 for the standard value was assumed.

The standard Manning's n for the river bed is nearly the same as mentioned in historical administrative reports for tributaries of the Neckar river. The specified roughness coefficients in historical times were calculated with the Ganguillet-Kutter equation (1), where v=flow velocity, n=roughness coefficient, R = profile radius and J=water surface slope (Königliches Ministerium des Innern 1896).

$$v = \frac{\frac{1}{n} + 23 + \frac{0{,}00155}{J}}{1 + (23 + \frac{0{,}00155}{J})\frac{n}{\sqrt{R}}}\sqrt{RJ} \qquad (1)$$

A calibration of the model was not possible because the stage-discharge relations are not known for the historical cross profiles. The discharges were calculated as sub-critical flow conditions. The HEC-RAS model uses the Mannig-Strickler equation for discharge estimation. In contrast, the historical discharges were calculated according to Harlacher's graphical method (Königliches Ministerium des Innern 1896).

Because the profiles are not associated to gauging stations, the indicated historical water level could potentially represent the level of the wash of the waves (energy head) and therefore overestimate the actual water level. Therefore, in the diagrams (Figs. 3–6) discharge values were also computed by using the energy line (EL) with the standard roughness. The discharges using the water surfaces (WS) were computed with three different roughness values (Table 2).

4 Results of discharge calculations along the Neckar for the 1824 and 1882 floods

4.1 Examples from greater Stuttgart

Profile Stuttgart-Cannstatt:

A cross profile and the stage-discharge in Stuttgart (Neckar River) is presented in Fig. 3. The flow discharge calculated on the basis of the standard Manning's n for 1824 ranges from 1610 $m^3 s^{-1}$ (energy line) to 2070 $m^3 s^{-1}$ (Fig. 5). Since the cross profile originates from the year 1877, there is no water stage available for the 1882 flood event.

Profile Münster:

Figure 4 displays the cross profile of the Neckar at Münster (5 km downstream of Stuttgart) at historical river km 186.47 and the corresponding stage-discharge curve determined with HEC-RAS. The figure shows the difference between the energy line and the water level as stage-discharge relations for the 1824 and the 1882 flood. The 1824 flow discharge ranges from 1800 $m^3 s^{-1}$ (EL) to 2170 $m^3 s^{-1}$ (WS). The discharges computed with high and low roughness values range from 1430 to 3100 $m^3 s^{-1}$ (both for the WS). The historical discharge determined by the official water authorities at the time is 1700 $m^3 s^{-1}$(Königliches Ministerium des Inneren, 1896). The calculated discharge for the 1882 flood event and standard Manning's *n* ranges from 1140 $m^3 s^{-1}$ (EL) to 1500 $m^3 s^{-1}$ (WS). The historical calculated discharge amount is 1250 $m^3 s^{-1}$ and falls within this range. The calculation with minimum and maximum Manning's *n* values results in a discharge of 910 $m^3 s^{-1}$ and 2100 $m^3 s^{-1}$, respectively.

4.2 Overview of the results obtained for the Neckar River

Figure 5 shows the results of the discharge calculations using HEC-RAS for the 1824 flood between river kilometre 80 and 220 and the historical calculations. In addition, the simulated discharges from Bürger et al. (2006) for the 1824 flood event and the discharge values for the current extreme flood (EHQ; LfU, 2005) are depicted. Since there are no documented water stages from any cross profiles further upstream, this particular river section was omitted in Fig. 5a. Due of the short distances between the cross profiles at Stuttgart (km 180) this section is magnified (Fig. 5b). For this section, the results from the HEC-RAS simulation using the EL and WS with standard roughness parameters match the historical calculations. Generally, this applies also for the whole Neckar River (Fig. 5a), except for the profile at Gemmrigheim (A3, river km 137), where all HEC-RAS simulations are much higher than the discharges from historical sources and the LARSIM model.

Figure 6 shows the results of the discharge calculations using HEC-RAS for the 1882 flood in comparison with the historical calculations. Since the availability of historical data in the former Kingdom of Württemberg is generally better in the second half of the 19th century, the profiles for this flood event are distributed more evenly along the Neckar River. In contrast, there are no cross profiles available at all for the river section in the former Grand Duchy of Baden, resulting in the discontinuation of the diagram at river km 100. Except for the profiles B8 and B9 (Table 1) in the upper course of the Neckar, where the flow area is relatively small, the discharges derived with HEC-RAS using the EL and WS with standard Manning's n correspond well with the values from the administrative reports (Fig. 6).

5 Discussion of the results

Discharge calculations from four different sources are available for three cross profiles in Stuttgart:

1. record 2577 from the City Archive of Stuttgart from 1877,
2. administrative report from the Interior Ministry of the Kingdom of Württemberg (Königliches Ministerium des Innern, 1896),
3. discharge simulation with the run-off model LARSIM (Bürger et al., 2006, 2007), and
4. calculations with HEC-RAS based on historical profiles from record 2577, City Archive Stuttgart.

Compared to the historical calculations for 1824 (a) at Stuttgart (Fig. 5, river km 189–187, 1370 $m^3 s^{-1}$), the streamflow from all HEC-RAS simulation runs (d) as well as the results from LARSIM (c) and the discharges from the administrative report (b) are higher. This example shows that a critical assessment of sources is necessary and it is inevitable to analyse all available historical data. The calculations from the administrative reports (b), with a value of 1700 $m^3 s^{-1}$ for this site, are similar to the results of the present study (1410–2380 $m^3 s^{-1}$) and identical with the EHQ (LfU, 2005). Bürger et al. (2006) reconstructed the hydrometeorological conditions of the 1824 flood event and simulated the resulting discharges with the current hydrological conditions of the Neckar River system (c). The flood discharge for this river section is approximately 1420 $m^3 s^{-1}$ and thus matches the value simulated with HEC-RAS using the energy line and standard Manning's *n* (d). Generally, the 1824 flood discharges simulated with LARSIM tend to underestimate the actual peak flood discharges, because the input data for this simulation was only available in daily resolution.

For the cross profile at Münster (river km 186), Bürger et al. (2006) determined a discharge of approximately 1700 $m^3 s^{-1}$. The calculations using HEC-RAS are within a range of 1430 to 3100 $m^3 s^{-1}$ depending on the roughness values and again discharge according to the energy line (1800 $m^3 s^{-1}$) with standard Manning's *n* is the value matching the LARSIM results. In comparison, the current HQ 100 determined by the water authorities for this site is about 1200 $m^3 s^{-1}$ (LfU, 2005).

The two discharges for the 1824 flood event obtained from historical cross profiles in the Grand Duchy of Baden range from 2500 to 5900 $m^3 s^{-1}$. The discharge using the water level and standard roughness is 4250 $m^3 s^{-1}$ for both profiles and using the energy line 4010 and 4080 $m^3 s^{-1}$, respectively .Thus, the flood discharge at this site was far higher than the current EHQ of 3600 $m^3 s^{-1}$ for the nearest current gauging station near Ebersbach-Rockenau at river km 60 (LfU, 2005). This discrepancy reflects the extreme magnitude of the 1824 flood event, especially in the lower course of the Neckar River, which is also documented in the historical sources (Bürger et al., 2006). The flood of 1824 was the most extreme along the Neckar River within the last 300 years and reached its highest water levels after the inflow of the river Enz at km 140. Based on the presented results, the historical discharges for the 1824 flood recorded by the local water authorities in the former Kingdom of Württemberg (Königliches Ministerium des Innern, 1896) and the Grand Duchy of Baden (Centralbureau für Meteorologie und Hydrographie, 1993) are plausible.

Unfortunately there were no historical cross profiles of the corresponding water levels available for the 1882 flood event for the lower section of the Neckar River in the Grand Duchy of Baden. The only available historical source (Centralbureau für Meteorologie und Hydrographie, 1893) states a discharge of about 3000 $m^3 s^{-1}$ for the city of Heidelberg (river km 26) which is slightly higher than the current HQ 100 (LfU, 2005) and seems to correspond to the intensity of the flood in this river section. Throughout the course of the Neckar River, the flood event of 1882 reached the intensity of the current HQ 100 and was lower than the flood in 1824.

For the 1824 flood, the temporal span between the actual flood event and the time of the survey, when the cross profiles were mapped, can reach up to 50 years, depending on the source of the cross profiles. Hence, we have to take into account that the historical discharge values for 1824 were approximated and the water levels were reconstructed since there were no gauging stations in operation at the time. Therefore, the indicated water level also could be related to the energy level of the cross profile, which Thorndycraft et al. (2006) also assumed for estimating palaeodischarges by sediment records. Figure 5 shows no significant correlation between EL or WS and the historical calculated discharges or the LARSIM results, respectively. Therefore, both values have to be taken into account when working with historical sources which were not derived at gauging stations. This is also the case of the 1882 flood event, although the discharge calculations were generally more sophisticated at this time, since there were several gauging stations in service. Nevertheless, the results allow no clear statement whether the EL or WS is the more suitable value for discharge calculations using historical data. Concerning the roughness parameters, the standard Manning's n produces the most feasible results.

6 Conclusions

The present paper completes the historical flood analysis presented by Bürger et al. (2006, 2007) for the Neckar River. The presented study shows that it is generally possible to estimate the discharge of historical floods using historical documents and to obtain details about the course and quality of a flood event. The results of this study and the historical discharges as well as the LARSIM results are comparable, so this method can be used to verify historical discharge calculations and, when no historical calculations are available, to obtain the discharges. By using various historical profiles, it is possible to cover large parts of a river course and recognize possible systematic errors in the sources. Hence, it is not reliable to use only a few cross profiles or data sources within a river system to obtain reliable information concerning a historical flood.

The 1824 event was the most extreme flood in large parts of the Neckar River, but the magnitude of the flood is not reflected by the current EHQ. The results from this study can contribute towards a better flood risk management in river catchments, because the knowledge about historical flood processes leads to a better understanding of flood processes.

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Table 1. Historical sources for cross profiles along the Neckar. Cross profile numbers A=1824, B=1882.

River/Administration	Data Source	Cross Profile			km
Neckar / Baden	General State Archive Karlsruhe (year unknown)	A1		Obrigheim I	82.50
		A 2		Obrigheim II	84.00
Neckar / Württemberg	Administrative reports (Königliches Ministerium des Innern 1896)	A 3	B 1	Gemmrigheim	137.04
		A 4	B 2	Münster	186.47
	City Archive Stuttgart (1877)	A 5		Bad Cannstatt I	187.00
		A 6		Bad Cannstatt II	187.22
		A 7		Bad Cannstatt III	188.34
	Administrative reports (Königliches Ministerium des Innern 1896)	A8		Plochingen	212.04
			B 3	Neckartenzlingen	234.43
			B 4	Tübingen	253.60
			B 5	Horb	288.30
			B 6	Aistaig	313.20
			B 7	Oberndorf	317.90
			B 8	Epfendorf	327.23
			B 9	Rottweil	344.00

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Table 2. Assigned Manning's *n* values for hydraulic modelling.

Surface description	Minimum Manning's *n* value	Standard Manning's *n* value	Maximum Manning's *n* value
channel	0.025	0.03	0.04
grass	0.025	0.035	0.05
trees	–	–	0.8

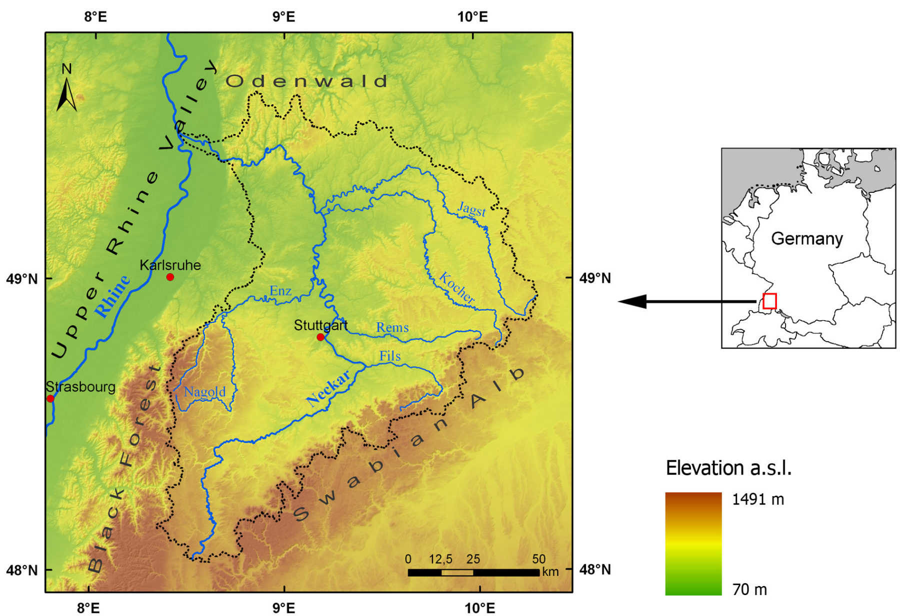

Fig. 1. Study area including the Neckar catchment (dotted black outline).

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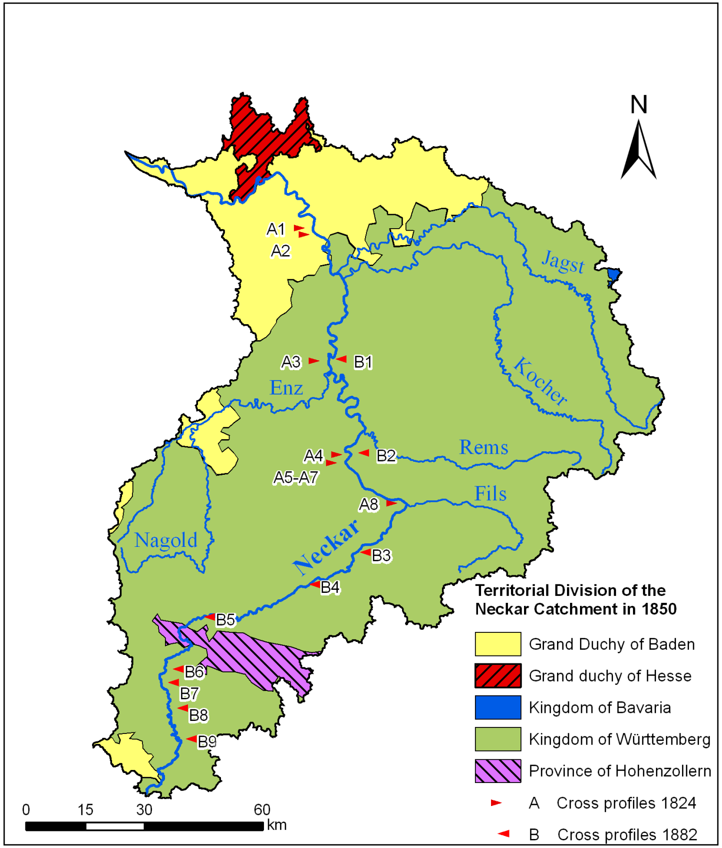

Fig. 2. Historical administrative districts in the Neckar catchment area and sites of the cross profiles (numbers according to Table 1).

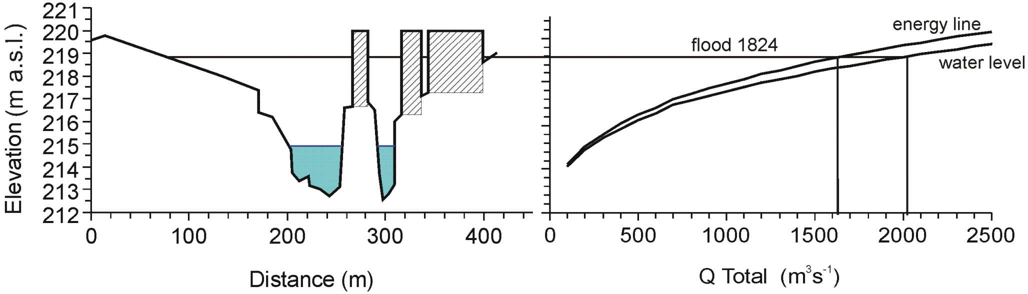

Fig. 3. Cross profile A5 from Stuttgart (Neckar River) with the stage-discharge curve and energy line (standard Manning's *n*) during the highest stage of the 1824 flood.

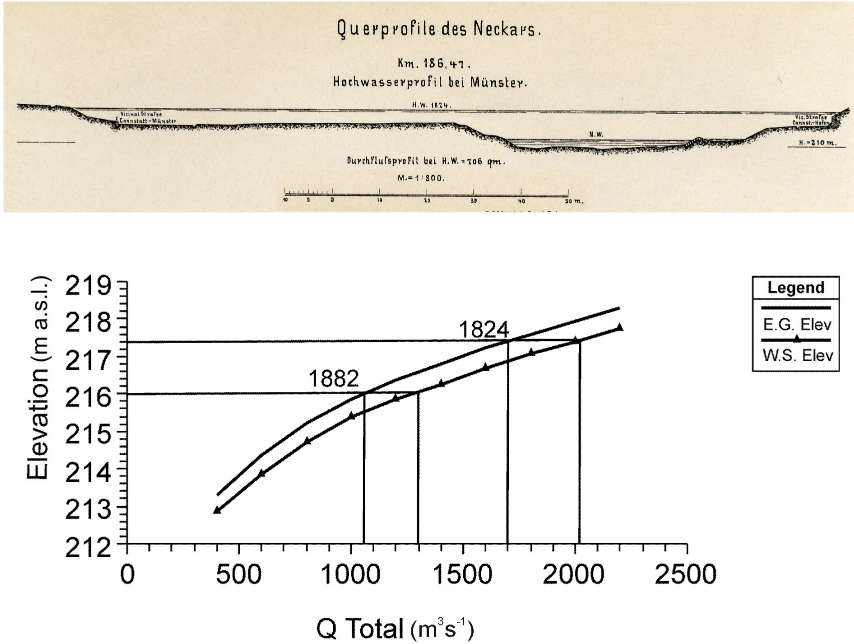

Fig. 4. Historical cross profile at Münster (A4/B2) (Königliches Ministerium des Innern, 1896) with the stage-discharge curve and energy line (standard Manning's *n*), indicated water stages for the floods of 1824 and 1882.

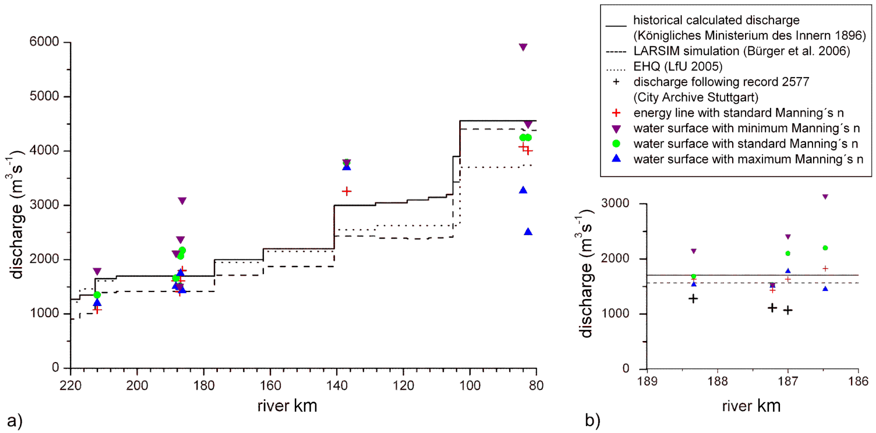

Fig. 5. **(a)** Discharges for the Neckar during the flood of 1824 from historical administrative documents (Königliches Ministerium des Innern, 1896), discharges simulated with historical cross profiles, LARSIM simulation by Bürger et al. (2006) and the current EHQ (LfU, 2005); **(b)** magnification for Stuttgart (km 189–186).

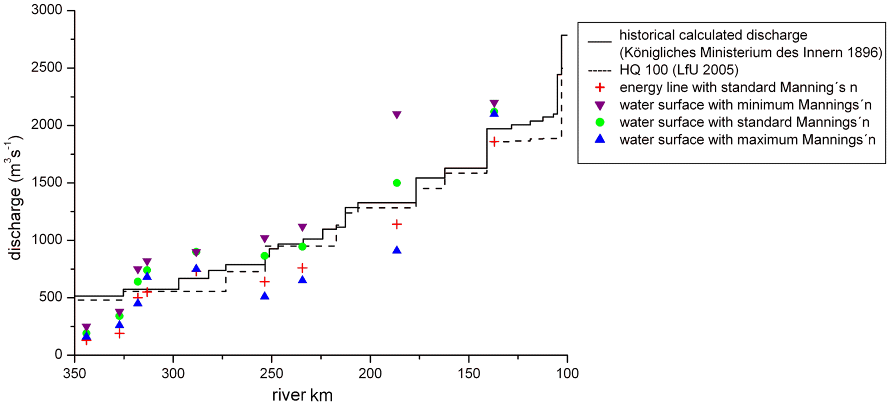

Fig. 6. Discharges for the Neckar during the flood of 1882 from historical administrative documents (Königliches Ministerium des Innern, 1896), discharges simulated with historical cross profiles and the current HQ 100 (LfU, 2005).

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