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Towards predicting catastrophic flood events: an analysis of historical data of rivers Elbe and Oder

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Abstract

Planning and taking precautionary measures against catastrophic flood events can be notably improved by deciphering their meteorological/climatological causes. For that purpose, analysing documentary data is undeniable. On the basis of Weikinn's Quellentexte, chronologies of flood events of rivers Elbe and Oder are constructed and critically tested, ranging from approximately 1021 and 1270, to 1851, respectively. Time-dependent occurrence rate is estimated using kernel functions. Pseudodata reduce boundary bias. Bootstrap confidence bands and a statistical test of hypothesis "constant occurrence rate" allow to assess the significance of results. Long-term socio-cultural signals (e. g., document loss) can be strongly reduced by a normalization. First results are presented. Elbe and Oder exhibit similar occurrence rates (increase until 1600, significant decrease until 1700–1750, new increase). Future research will include differentiation (winter versus summer floods), magnitude classification and extending data coverage from 1851 to the present.

Zusammenfassung

Planungs- und Vorbeugemaßnahmen gegenüber katastrophalen Hochwasserereignissen können durch ein kausales Verständnis deren meteorologischen/klimatischen Ursprungs deutlich verbessert werden. Hierzu ist eine Analyse historischer Daten unerlässlich. Für die Flüsse Elbe bzw. Oder werden auf Grundlage der Weikinnschen Quellentexte kritisch geprüfte Chronologien der Hochwasserereignisse von ca. 1021 bzw. 1270, bis 1851 erstellt. Die zeitabhängige Auftrittsrate wird mit Kernfunktionen geschätzt. Pseudodaten reduzieren systematische Randfehler. Bootstrap-Konfidenzbänder und ein statistischer Test der Hypothese „konstante Auftrittsrate" erlauben eine Beurteilung der Signifikanz der Ergebnisse. Langfristige sozio-kulturelle Einflüsse auf die Daten (z. B. Dokumentenverlust) lassen sich durch eine Normierung deutlich reduzieren. Es werden erste Ergebnisse vorgestellt. Elbe und Oder zeigen ähnliche Verläufe der Auftrittsrate (Anstieg bis 1600, signifikanter Abfall bis 1700–1750, erneuter Anstieg). Zukünftig geplant sind: Differenzierung in Winter- und Sommerhochwässer, Stärkeklassifizierung sowie Datenanschluss von 1851 bis heute.

Introduction

Floods have a considerable damage potential. Analysing factors (climate, human) which influence their rate of occurrence is a prerequisite for building climate models aimed to predict such extreme events—an essential tool for planning and taking precautionary measures.

In the years following the Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (Houghton *et al.* 1996) speculations grew that the occurrence rate of floods may have changed in the past decades, and that this change be related to a change of global climate (e. g., Olsen *et al.* 1998, Easterling *et al.* 2000). It is further currently being realized that the nonstationary character of a climate change has to be considered when analysing extreme events and their occurrence rates in meteorology and climatology (Olsen *et al.* 1998). Finally, it seems that the understanding is growing that, in a world of limited climate data and coarse climate models, estimated quantities without error bars or confidence intervals have little use for assessing results and evaluating consequences (Allen *et al.* 2000).

To analyse a relation between climate and flood occurrence rate it is of essential importance to use documentary data since these range back several hundreds of years—longer than any river gauge measurement. However, analysis of such data has to take into account certain aspects such as perception bias or loss of documents. Analysis and interpretation of historical flood data is thus multi-disciplinary: history, meteorology and statistics.

Data material

Basis of the data used are the source texts of Curt Weikinn [1888 to 1966] (1958 ff). In this work Weikinn collected reports about, amongst many other meteorological/climatological elements, inundation, floods and freezing of rivers, with emphasis on central Europe. The texts consist of excerpts of contemporary scientific literature, chronicles and other publications on local history and geography. It was important to Weikinn that "his" authors themselves used original documents.
We restricted the construction of our flood-event database to the Middle Elbe (from Litoměřice to Magdeburg) and the Middle Oder (from Racibórz to Kostrzyn) since these parts are well documented and further exhibit good spatial correlations of flood events along the affected river courses (e. g., Fischer 1907). The most important sources in Weikinn for our purpose were: in case of the Elbe, Pötzsch (1784–1800) and Schäfer (1848) (both consulted also in original), Katzerowsky (1883, 1895), Pohle (1886), Bertram (1865), Schmidt (undated), Kleber (1909); in case of the Oder, Matthias (1849), Pol (1813/24) and Schmidt (1922).
Spacious and grave floods are characterized by a large number of (usually dramatic) descriptions. From such sources even the whole course of flooding may be deduced. A good example is the Oder flood of 1736 (Militzer *et al.* 1999). Minor events, on the other side, may have been captured by only a few reports, increasing the risk that they become lost or that a wrongly noted year is not identified. To minimize the risk of including such false reports we therefore checked the Weikinn texts for supporting meteorological reports (preferably from a different source) such as precipitation, floods in tributaries, freezing etc. In case of the Elbe, we excluded 34 from 288 events, in case of the Oder 36 from 146. All excluded events were of minor magnitude. Reliable reports about Elbe floods date back about 980 years; in case of the Oder about 730 years.

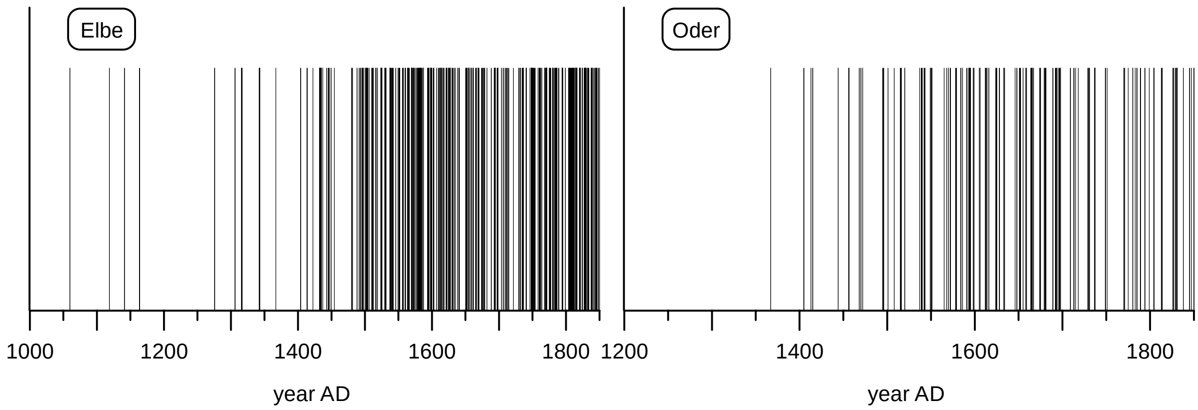

Figure 1: Data material: flood events in rivers Elbe (n = 254, observation interval: t1 = ca. A.D. 1021, t2 = A.D. 1851) and Oder (n = 110, observation interval: t1 = ca. A.D. 1270, t2 = A.D. 1851).

Method

The advantages of using a kernel estimate of occurrence rate instead of a histogram are well known in statistics and demonstrated by Mudelsee *et al.* (2001) in case of flood events of river Oder. The problems of using histograms are illustrated by asking the following questions:

- Why does a decade start at, say, 1810, and not at, say, 1813?
- Why not use a, say, 22-year binning instead of decades?
- The histogram produces an unsmooth estimate of occurrence rate. Is that likely to reflect the true natural behaviour?

Kernel occurrence rate estimation uses a smooth kernel function, K (here: a Gaussian), to weigh observations. The occurrence rate, l_y, can be calculated over a pre-defined grid of points, l_x, at arbitrary spacing:

$$l_y(l_x) = \sum_{i=1}^{n} K_h(l_x - t(i)), \qquad K_h(\cdot) = K(\cdot / h) / h,$$

where $t(i)$ are the extreme event dates, n is the number of events and h is the kernel bandwidth.

A major problem is choice of kernel bandwidth. However, this can be solved using cross validation (Brooks and Marron 1991), that is, the cross-validated bandwidth, h_{CV}, yields an optimally balanced (bias/variance) estimate. h_{CV} thus minimizes the cross validation function,

$$CV(h) = \int_{t1}^{t2} l_y(l_x)^2 \quad - \quad 2\sum_{i=1}^{n} l_{y,h,i}(t(i)),$$

where

$$l_{y,h,i}(l_x) = \sum_{\substack{j=1,\\ j\neq i}}^{n} K_h(l_x - t(j))$$

is the leave-one-out estimator. $t1$ is the lower bound of the interval over which the observations where made, and $t2$ is the upper bound.

Of considerable interest is to have a confidence band around the estimated occurrence rate (see Introduction). This paper adopts standard bootstrap simulations to achieve that aim: From the original set of points (extreme event dates), draw (with replacement) a sample of same size. Estimate the occurrence rate for simulated data. Repeat the procedure, say, 10 000 times in total. The variability of estimated occurrence rates allows to construct confidence bands (level α) using percentiles.

Kernel occurrence rate estimation and confidence band estimation used here closely follow the methods developed by Cowling *et al.* (1996), implemented into the Fortran 90 computer program XTREND (Mudelsee (in press)).

It is further possible to test the null hypothesis

H0: constant occurrence rate over time

versus the alternative hypothesis

H1: decreasing (increasing) occurrence rate,

using the test of Cox and Lewis (1966). Under H0, the variable

$$\frac{\sum_{i=1}^{n} t(i)/n-(t1+t2)/2}{(t2-t1)\cdot\sqrt{[1/(12\cdot n)]}}$$

tends rapidly to normality which enables a simple and efficient test.

Results

Elbe and Oder exhibited cross validation functions (Figure 2) with h_{CV} similar in value (Elbe: 25.5 years, Oder: 59.6 years). That allowed using the same kernel bandwidth (h = 40.0 years) for occurrence rate estimation (Figure 3), that is, both curves show the same amount of smoothing.

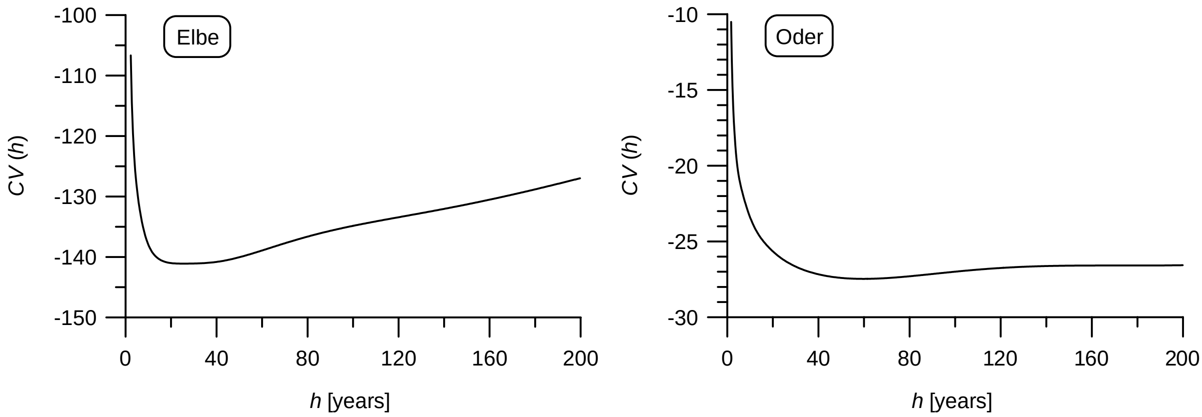

Figure 2: Cross-validation functions.

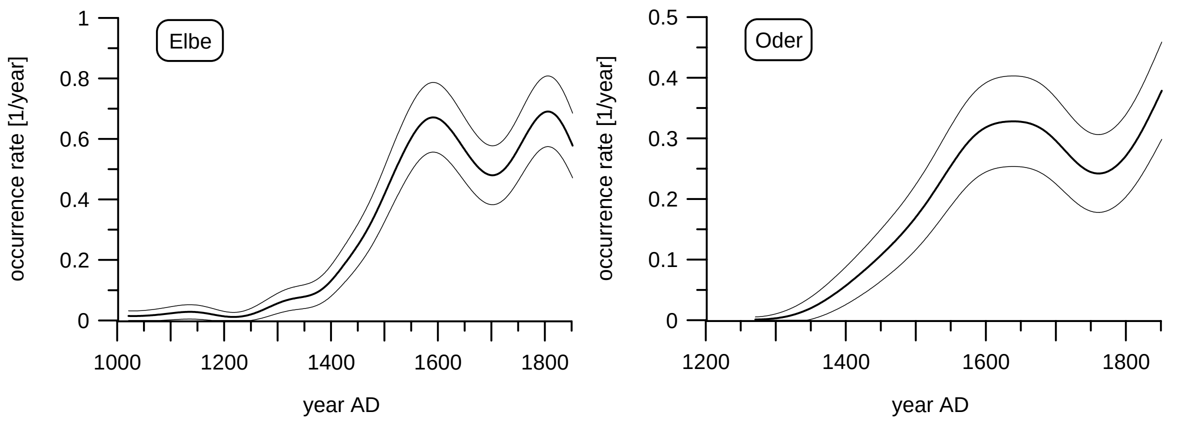

Figure 3: Occurrence rates (heavy lines) with α = 90 % confidence bands (light lines), estimated using h = 40 years. Number of bootstrap simulations: 10 000.

Both rivers exhibit similar occurrence rate curves (Figure 3). A strong increase until about A.D. 1600, a significant (at 90 % confidence level) decrease until about A.D. 1700 to 1750, followed again by an increase. Whereas in case of the Oder this increase seems to persist, the Elbe shows a further decrease, from about A.D. 1800 onwards. The Elbe floods, in general, have a higher occurrence rate (about twice) as the Oder.

The most likely cause for the strong increase until about A.D. 1600 seems to be socio-cultural and not climatic. Perception of floods may have changed over time, the interest to note such events thereby increasing after humanism and the scientific revolution of, say, Nicholas of Oresme, Copernicus, Galileo and Kepler. Second, old documents simply have worse chances than newer to survive in the course of time and find entrance in secondary sources. It is reasonable to assume that the timescale of socio-cultural changes is longer (a few hundred years) than that of short-term weather/climate changes (Pfister *et al.* 1999). With this assumption it is possible to extract the socio-cultural signal from the occurrence rates and use it for normalization.

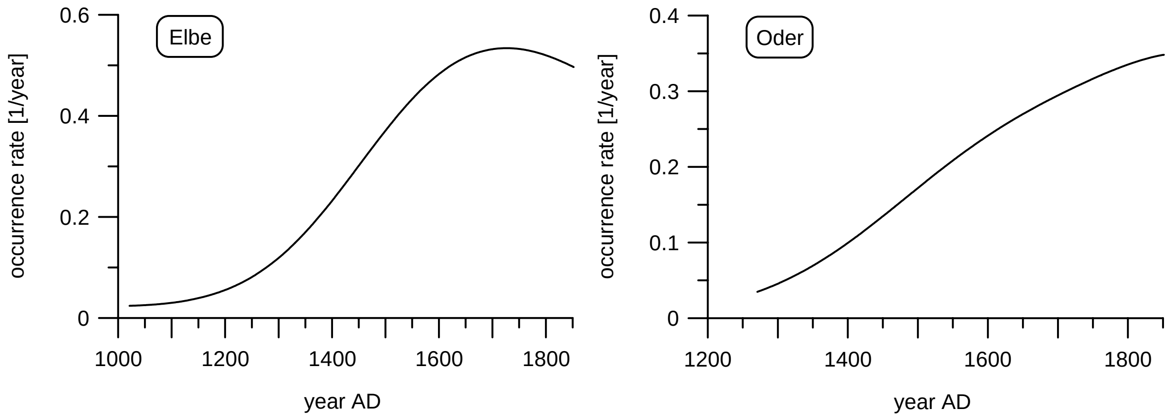

Figure 4: Occurrence rates, estimated using h = 150 years.

Figure 4 shows the socio-cultural signal of occurrence rate, estimated by using a large kernel bandwidth (150 years). We use this curve for normalization, that is, we divide the curves in Figure 3 (occurrence rates, estimated using h = 40 years) by their respective counterparts in Figure 4. The resulting normalized curves (Figure 5) consist mainly of shorter-term variability and should ideally be free of socio-cultural influences. The negative but inevitable aside of this normalization is that also long-term climatic changes have been removed. (Nearly identical results are obtained using h = 100 or h = 200 years for normalization.)

For the Elbe, a local maximum in occurrence rate results at around A.D. 1100 (Figure 5). However, due to the sparse data there, the confidence band is rather large. The „trough" in occurrence rate at around A.D. 1200 to 1250 seems to reflect a real feature although we remain sceptical about its duration. Adding a single hypothetical flood event at A.D. 1225 resulted in low normalized occurrence rates from around A.D. 1200 to 1400 (results not shown). Thus, estimation results in that part of the curve are rather susceptible to recording errors. The other features (high around A.D. 1600, low around A.D. 1700, high around A.D. 1800, followed by a decrease) occur similarly as in Figure 3.

For the Oder, the increase in occurrence rate until about A.D. 1600 has been drastically reduced by the normalization (Figure 5). The general shape since then (high around A.D. 1600, low around A.D. 1750, followed by an increase) is similarly as that in Figure 3.

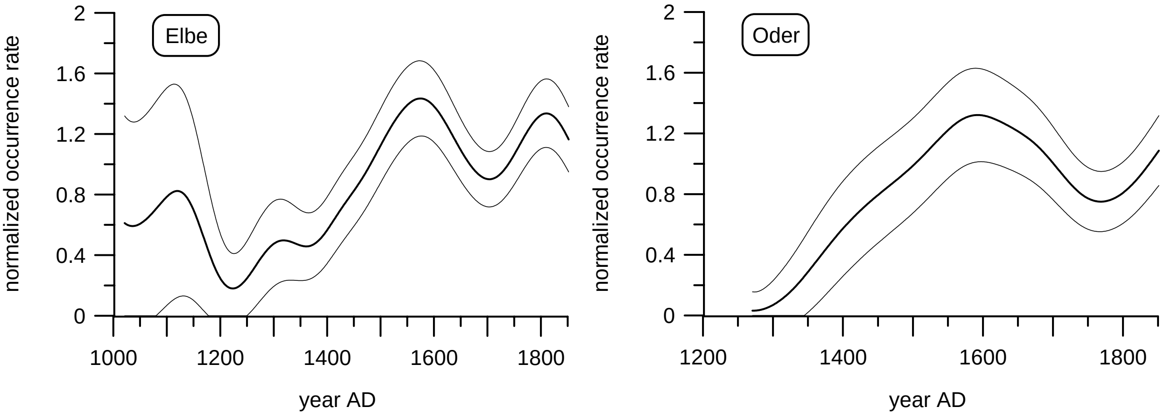

Figure 5: Normalized occurrence rates (heavy lines) with 90 % confidence bands (light lines), using h = 40 years (estimation) and 150 years (normalization).

Pseudodata

Since the extreme event times, t, are restricted to the observation interval, [$t1$; $t2$], boundary effects (that means, reduced occurrence rate) will result near (within $\approx 3 \cdot h$) the boundaries. This bias may be severe in case of occurrence rate estimation (in contrast with density estimation) because the observed process may continue outside the observation interval.

A computationally efficient method to reduce boundary effects is to generate pseudodata outside of [$t1$; $t2$]. The simplest pseudodata generation method is reflection of data at the boundaries. Evidently, the reflection method fails to take into account a nonzero slope of l_y. The advanced pseudodata method of Cowling and Hall (1996) overcomes this problem by extrapolating the empirical distribution function of t. Cowling and Hall (1996) found via a Monte Carlo simulation study that their pseudodata method outperforms other methods devised to reduce boundary effects. The occurrence rate estimations here use Cowling and Hall's (1996) method. Figure 6 demonstrates the superiority of that method over reflection method which fails to reproduce the slope (Elbe: decrease; Oder: decrease) of l_y at $t2$.

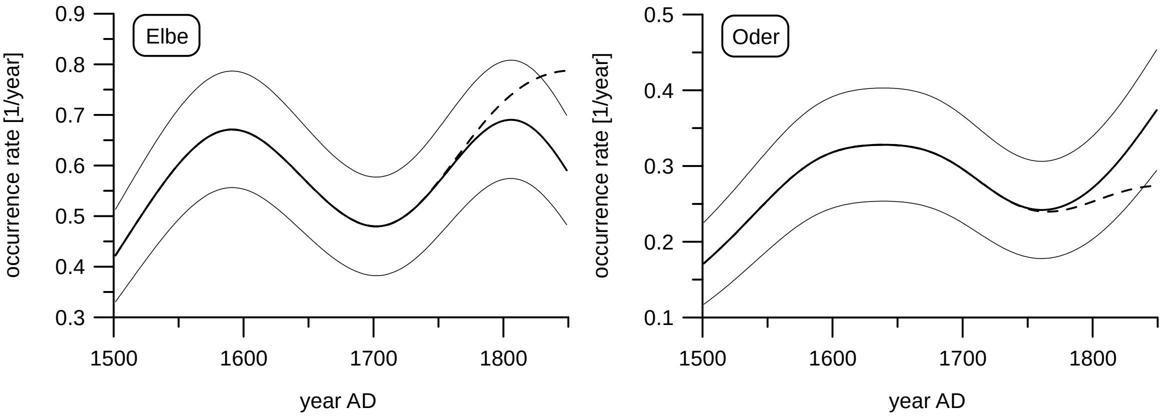

Figure 6: Comparison of pseudodata generation methods, h = 40 years. Advanced method („threepoint" in Mudelsee (in press)) (solid lines; cf. Figure 2) versus reflection method (dashed).

Future research

The aim of our research is to infer the climatological forcings of extreme flood events in rivers Elbe and Oder. These factors could then force climate models designed to predict flood events in future, providing invaluable information to protect life and economy in the affected areas. To achieve the aim, however, the following points have to be taken into account.

Winter versus summer floods. Winter floods in both Elbe and Oder are mainly directly caused by strong winter precipitation, freezing and subsequent thawing; summer floods by long and heavy rainfall (e. g., Fischer 1907). This was also our finding when analysing the Weikinn texts. The above occurrence rate estimations will therefore also be carried out for winter and summer floods separately.

Magnitude classification. It is useful to respect the varying strength of flood events. Since documentary data as Weikinn's are mostly qualitative, only a few magnitude classes can be used. We follow Brádzil *et al.* (1999) and use three classes. It is expected that for stronger flood events (class 2 or 3) perception bias or document loss is weaker than for class-1 events.

Data extension. Weikinn's data end with 1850. It is obvious that extending flood event data up to the present is important. In case of the Elbe we use river gauge data from the Königliche Elbstrom-Bauverwaltung (1893) which cover the interval 1851 to 1891, daily runoff data for Dresden from the Global Runoff Data Centre (GRDC) (Koblenz, FRG) which cover the interval 1852 to November 1999 and press releases of the Amt für Presse und Öffentlichkeitsarbeit der Landeshauptstadt Dresden (http://www.dresden.de/rootger/pmindex/03/e34.html) which start in June 1998. Conversion of runoff data into river gauge data is achieved using the flood data for Dresden (runoff, gauge level) of the Sächsisches Staatsministerium für Umwelt und Landwirtschaft (1999) (Figure 7). (Data from these sources in overlapping segments agree extremely well.) Similar work for the Oder is in progress.

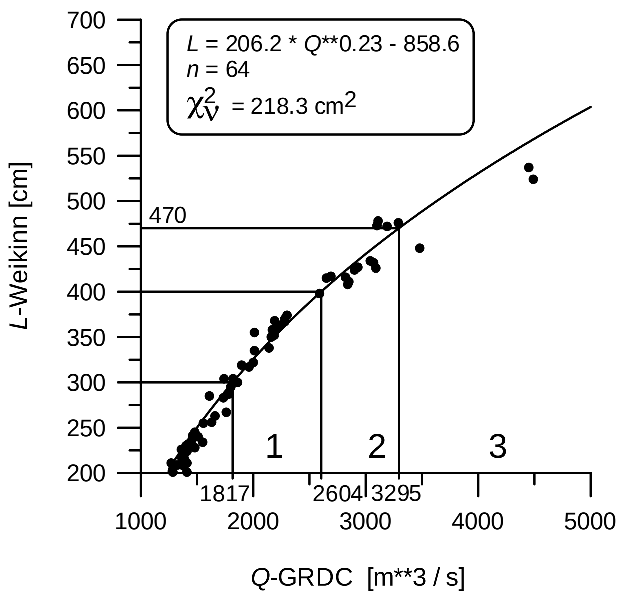

Figure 7: Conversion of runoff data (Q) from the GRDC into gauge levels (L), Elbe (Dresden). Magnitude classification follows that of Weikinn's documentary data. The square root of reduced chi-squared is approximately 15 cm, that is, not larger as the uncertainty expected for a gauge measurement. Thus, the fit is of good quality.

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