Estimation of peak discharges of historical floods

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Abstract

There is no doubt, that the hazard assessment of future floods especially under consideration of the recent environmental change can be significantly improved by the consideration of historic flood events. While flood frequency inventories on local, regional and even European scale are already developed and published, the estimation of their magnitudes indicated by discharges is still challenging. Such data are required due to significant human impact on river channels and floodplains though historic flood levels cannot be related to recent ones or recent discharges. Based on own experiences from single local key studies the general outline of an approach to estimate the discharge of the previous flood based on handed down flood level and topographic data is presented. The model for one-dimensional steady flow is based on the empirical Manning equation for the mean flow velocity. Background and potential sources of information, acceptable simplifications and data transformation for each element of the model-equation are explained and discussed. Preliminary experiences on the accuracy of ±10% are documented and potential approaches for the validation of individual estimations given. A brief discussion on benefits and limitations including a generalized statement on alternative approaches closes the review presentation of the approach.

1 Introduction

Water level data from previous 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. Recently, the European Union approved a flood risk estimation guideline that regulates by law the quantitative consideration of previous floods (EU 2007). Previous floods can be divided into historic and palaeofloods. The difference is based on the duration of historic times with handed down historic documents or descriptions while palaeoflood events took place in prehistoric times. Note, that in several previous publications (e.g. Benito et al. 2010, Brázdil et al. 2006, House et al. 2002, Thorndycraft et al. 2005) the term "palaeoflood" is used even for recent flood events quantified by indirect methods due to missing gauging stations. According to the established used of the prefix "palaeo" based on the old-Greek origin "palaios" meaning "old" e.g. in palaeoclimatology or palaeohydrology a stricter only temporal differentiation seems more logical. Historic times with detailed flood descriptions last for about one or two centuries e.g. in many parts of North America up to several millennia in the old cultures of ancient Egypt or China (e.g. Bell 1970; Pang 1987; Herget 2012). Consequently, the time of the transfer of historic times flood events to palaeofloods differs regionally. Typically, most historic floods can be dated exactly with high temporally and partly also spatial resolution reaching levels of hydrograph reconstructions with a temporal resolution up to minutes based on historic photographs (Roggenkamp and Herget 2014). Temporally, palaeoflood evidence based on sedimentary or geomorphological remnants (e.g. Baker et al. 1988, Herget 2012, House et al. 2002) can only be estimated using relative chronologies or physical based dating techniques like radiocarbon or optical stimulated luminescence and give less exact dates but might reach even annual resolution for the entire Holocene times if dendrochronological data from trees rings in flood plains or varves in lakes are available (e.g. St. George and Nielsen 2002, Stoffel et al. 2010, Corella et al. 2014). Palaeofloods can be analysed back troughout Earth's geological history but decrease by number and resolution in pre-Pleistocene times based on the less significant sedimentary evidence (e.g. Herget 2012, House et al. 2002) while the also quantitatively reconstructed extraterrestrial flood and drainage events date back in astronomical timescales of billion of years (e.g. Burr et al. 2009). Here, a focus is given on historic floods in Europe as their evidence and their relation to recent and near future floods conditions are more obvious than for palaeofloods from geological times.

Historic flood levels can be found as markings on historic buildings (Fig. 1), identifying the maximum flood level, or in documentary sources (Deutsch et al. 2010). Usually, written descriptions compiled in source text compilations (e.g. Alexandre 1987, Weikinn 1958, www.tambora.org, Buisman and Van Engelen 1995) are qualitative, such as "… in consequence of the flood, great damage was affected along the river at …" but also semi-quantitative descriptions like " … the water reached the doors of the church" are preserved. After careful interpretation and analysis, many can be used as flood level indicator for historic times as is the case for rivers in Europe (e.g. Brázdil et al. 2012, Glaser et al 2010, 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. Benito and Thorndycraft 2005; Kidson and Richards 2005; Savenije 1995). 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 (e.g. Herget et al. 2005). 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. Benito et al. 2003, Brázdil et al. 1999, 2005, 2006; Glaser et al. 2010; Thorndycraft et al. 2003) while some exceptions prove this rule (e.g. Elleder 2010; Elleder et al. 2013, Herget and Meurs 2010; Macdonald et al. 2006; Roggenkamp and Herget 2014; Wetter et al. 2011).

Below, a review on a simple, suitable and more or less easy applicable approach to estimate the discharge of previous floods based on preserved water level data is presented. The method of the calculation itself with a focus on the determination respectively estimation of the parameters is given in detail below and commented based on own experiences from previous applications of the approach in several local key studies. A discussion on limits and advantages in comparison to other approaches completes this review.

2 The method and parameter determination

Inserting the empirical Manning equation for mean flow velocity v (Chow1959) into the continuity equation describing discharge Q as product of cross-section area A and flow velocity v, discharges for specified stages of historical flood events can be calculated as

$$Q_i = A_i \, R_i^{2/3} \, S_i^{1/2} \, n_i^{-1} , \qquad (1)$$

with Q_i discharge [m³/s], A_i cross-section area [m²] of the floodplain area for the specific flood level, R_i hydraulic radius [m] for the flood level determined as quotient of the cross-section area A_i [m²] and the wetted perimeter P_i [m], S_i energy line slope [m/m] and n_i hydraulic roughness coefficient [-] according to Manning.

For different stages of a flood event, most of the factors of the equation vary (cf. the following subchapters) and therefore have to be related to a specific stage, e.g. the maximum one of the peak discharge as handed down by most flood marks. Due to the empirical character of the Manning equation, equation (1) is not true by units (cf. Chow 1959 for details and discussion). As equation (1) determines the discharge related to a specific stage of a flood, a uniform one-dimensional steady flow is modelled. Ice-jam related floods (Beltaos 2008; 2014) cannot be quantified by the approach due to the temporal blockage of the channel as reason for the flood level instead of an increased discharge.

By a closer look, floodplains of river valleys consist of several units with significantly different hydraulic roughness caused by obstructions like buildings or vegetation, surface roughness by minor landforms like floodplain channels or hills and depressions in addition to different land use (Fig. 2). Generally speaking, the units of settled areas, the river channel and the floodplain provide obviously different hydraulic roughness. Additionally, they developed and changed differently in historic times, so have to be considered individually. The floodplain can be further subdivided into open ground of agricultural use, flood plain channels eroded and incised by previous flood events and floodplain forests with dense vegetation cover dominated by trees and bushes. Consequently, the discharge is calculated separately for individual homogenous units of the inundated cross-section area A and subsequently summarized to a single value for the flood event. Each of the units have to be reconstructed for its appearance and hydraulic roughness at the point of time the historic flood event occurred. Uniform flow within each unit is assumed.

Within each of the units the parameters of equation (1) are quantified according to the scheme illustrated in Figure 3 and explained in detail individually below. In case significant uncertainties arise already for the flood event itself – e.g. different water levels from different reliable and verified sources or missing information if the debris of a destroyed stone bridge filled and blocked the river channel during the flood event or not (cf. Herget et al. 2014 for details of these problems related to the July 1342 flood event) – different scenarios based on varying assumptions should be considered. Arguments for or against the plausibility of the individual scenarios can be based on the derived discharge calculations and their relation to discharge calculations at additional locations up- or downstream along the river for the same event.

2.1 Cross-section area A

As illustrated by Fig. 2, the level of the specific flood of interest dominates the magnitude of the cross-section area A. The reconstruction of the topography of the inundated floodplain area is based on data from historic maps, etchings and drawings. Typically, locations of historic importance with verified flood marks are already investigated rather detailed for their urban archaeology with accessible compilations of historic documents on the appearance of the area. Based on these illustrations and archaeological studies, any significant topographic change – including land use change on the floodplain and expansion of the settlement – can be backtracked qualitatively and partly even quantitatively by the thickness of time-specific sedimentary layers through time. For reference, modern large-scale topographic maps with detailed elevation data can be used and differences by erosion or accumulation through time quantified along the profile of the cross-section area. Based on own experiences it is recommended to transfer all data into metric units and relate them to metres above sea level as local reference points like gauge datum, measurement units and calibrations like map datum were changed through historic times. Using of relative values like height above gauge datum might be a source of confusion.

According to elevation changes, the separated units of the inundated floodplain (Fig. 2) show different characteristics and require detailed investigations. For the areas of the settlement itself, a tendency of accumulation can be observed. Background is the typical repeated rebuild of historic settlements after destruction by fire, war or systematic modernisation on top of the remnants and debris of the previous buildings. Especially measures for the stabilisation of shorelines at harbour areas result in significant accumulation to protect against minor floods. In Cologne, an anthropogenic embankment of the nearshore areas towards the River Rhine of locally up to 10 m for the last 2000 years since Roman times can be observed (Herget and Meurs 2010). Due to anthropogenic measures, changes within the settled areas took place at certain points of time while in the neighbouring river channel and on the floodplain more or less continuous rates of aggradation or erosion can be observed. Destructive single events like e.g. the July 1342 flood resulting from intensive erosive rainfall with locally enormous accumulations of colluvial deposits (Bork 2014, Kiss 2009, Zbinden 2011) illustrate the complexity of the phenomenon. Anyhow, for urban areas where the long-lasting handed down flood level history is localised the simplification of the trends mentioned above provides a framework for potential results of detailed local investigations.

As most large river channels are excavated to improve navigation and narrowed to provide space for additional settlements, the natural conditions are rarely preserved. Due to missing systematic investigations and measurements data on natural river channel geometry from historic times are rare. Only occasionally, systematic bathymetric measurements were carried out and documented in detail and could be considered in detail for channel reconstructions (e.g. Elleder et al. 2013; Herget and Meurs 2010). Frequently, reports and plans about how to improve river channel conditions in the historic near future provide data about maximum values of natural channel depths as the excavated channels will be deeper than the natural ones. If no historic maps or paintings more or less true to scale exist, the construction and lengths of bridges might support first estimations of historic channel widths (BGU 2011). Based on oldest data on channel geometry, previous conditions can be estimated by the extrapolation of handed down geometry considering natural incision or aggradation rates. Theoretically, numerous aspects like change of trends by tectonic movement, climatic change or lands use change resulting in varibility of the hydrology and sediment budget might be expected to cause serious troubles for such extrapolation. On the other hand, the time period back to the earliest historic flood events with sufficient data for a quantitative reconstruction in Europe date back to late medieval times. Annual natural rates of incision of rivers of e.g. 1 mm/a – which is a rather unrealistic high value considering differences in altitude of river terraces (Bridgland and Westaway 2008, Schirmer 1995) – would result in a difference of some decimetres. Regarding we are dealing with high magnitude deep water floods inundating flood plains of several kilometres width, depth variations of such dimension in the relatively narrow river channel itself do not influence the dimension of entire cross-section area significantly (cf. e.g. Elleder et al. 2013 or Herget and Meurs 2010 with different observations on natural river channel trends in historic times). Note, that this preliminary assessment should not be transferred arbitrarily on any river channel as globally speaking extremer trends like more or less natural aggradations of >10 m in just one century are also observable (Qingchao 1989).

The width of the neighbouring floodplains in historic times might be considerable underestimated as dykes allowed the expansion of settlements and the installation of infrastructure (Schenk 2001). E.g. the width of the natural floodplain if the River Rhine at Cologne is about 9000 m while the recent distance between the dykes respectively higher terrace levels is down to 350 m (Herget and Meurs 2010). The floodplains have the tendency to rise by the deposition of suspension load during floods. The accumulation of the sediments might have reached significantly thickness but must be differed by age. Geological and soil maps respectively archaeological excavations provide suitable information on the age of the floodplain deposits. Like for the river channel incision, a closer look to elevation changes derived from extrapolated aggradation rates illustrate a minor influence for broad floodplains in Europe. Local exceptions related to extreme events like the 1342 flood mentioned above or the famous rise of the valley bottom of 3.9 m since about 1210 at the village of Grünsfeldhausen located in a small valley 10 km southwest of Würzburg indicated by the level of the entrance of the church below the surface (Hahn 1992) are again exceptions of the rule. On the other hand, these examples illustrate again the necessity of careful investigation for local studies.

2.2 Hydraulic radius R

The hydraulic radius is calculated as R = A / P, where A is cross-section area and P is wetted perimeter. It considers the shape of the cross-section area as along the shores and the channel bottom, roughness elements decrease the mean flow velocity. Like the cross-section area, the wetted perimeter can be determined from modern topographic maps considering the same properties of the features along the profile as discussed for the cross-section area.

2.3 Slope S

Strictly speaking, the slope S is the slope of the energy line along the flow direction (Chow 1959). By a closer look and along river section of sufficient length the slope of the water surface and the energy line are parallels, which significantly ease the quantification. Within the region of the cross-section profile no significant backwater effects by narrow culverts at bridges, or other obstructions like mills or weirs including cliffs at the channel bottom should influence the water level at flood stage. If no significant obstacle were introduced since the occurrence of the historic floods of interest, the recent slope of the water surface can be taken over as incisions or aggradations occurred over a longer section resulting in a parallel rise or lowering of the energy line. For a known slope S and assurance that the water level was not influenced along the way, heights of flood level marks from other locations within the area of the study can be transferred to the cross-section profile. Note, that their absolute height must be modified considering the value of the slope.

2.4 Hydraulic roughness n

The hydraulic roughness reducing the mean flow velocity is quantified by empirical values based on experiences and available from tables and manuals (e.g. Arcement and Schneider 1989, Barnes 1967, Chow 1959). Chow (1959, 101f) analysed the elements affecting the hydraulic roughness and found the principal algebraic form of:

$$n = (n_1 + n_2 + n_3 + n_4 + n_5 + n_6 + n_7 + n_8 + n_9)\, m \qquad (2)$$

where n_1 represents surface roughness, n_2 vegetation, n_3 channel irregularity, n_4 channel alignment, n_5 obstructions, n_6 silting and scouring, n_7 stage and discharge, n_8 sediment load (density of water), n_9 seasonal changes, and m represents a correction factor for channel meandering.

Assuming, that the sediment load did not reach concentrations of hydraulic influence like hyper-concentrated flow during the historic flood event of interest and considering the steady flow conditions modelled, the summands n_6-n_9 do not require further consideration. Consequently, equation (2) is simplified to

$$n = (n_1 + n_2 + n_3 + n_4 + n_5)\, m \qquad (3)$$

These roughness elements are components reducing the mean one-dimensional flow velocity by turbulences. Surface roughness n_1 is caused by larger or smaller grain size of the sediments at the channel bottom up to minor submerged obstacles. The influence of vegetation n_2 obviously changes throughout the year, hence differs for the same floodplain by season. Channel irregularities n_3 are typically submerged bedforms influencing the vertical component of the current above like local scour holes, sedimentary bars or riffles and pool structures. The channel alignment n_4 is the similar horizontal effect generated by any difference of the lateral shores from a straight line. Obstruction n_5 are even large obstacles within the channel or floodplain that even might reach from the bottom up to the surface of the flood level like trees or houses. Any deviation of the river channel or floodplain orientation from a straight line like a meander generates secondary currents which reduce the main one-dimensional flow velocity. Hence, the degree of the deviation from straight is proportional to a value of m>1, which increases the roughness and decreases the mean flow velocity.

From the references mentioned above, values for each component of equation (3) can be taken. The degree of the strength of the roughness characteristic varies and requires experiences on the estimation of the representative value. Therefore, in the source tables data ranges with minimum, typical and maximum values for classified degrees of the development of each element are given. As it is already challenging to estimate a suitable roughness value for recent channels, the limited detailed information on historic channel conditions increases the uncertainty significantly. Consequently, the range of n-values is taken over into the final discharge calculation resulting in minimum (for upper range roughness), maximum (for lower range roughness) and a plausibly balanced representative value for each roughness component (Fig. 3). The according to all available information balanced value of n_p is not necessarily the mean value between n_{min} and n_{max}, but frequently is arbitrary chosen so due to missing detailed information. For each unit of the cross-section profile, three roughness values of a range of $n_{min} < n_p < n_{max}$ are estimated to take into account the individual aspects of hydraulic roughness, consequently resulting in three discharge values that are finally summarized to the flood discharge.

Based on own experiences from previous key studies, the different units of a cross-section have specific roughness characteristics, which are briefly summarized:

Frequently, flood water in inundated modern cities with relatively broad straight roads compared with medieval town is standing and not flowing through town (e.g. Elleder et al. 2013, Herget and Meurs 2010, Roggenkamp and Herget 2014). Obviously the roughness exceeds a threshold and hinders the water to flow as fast as on the open floodplain or within the river channel. Considering that most historic towns were fortified by a surrounding city wall and typically featured narrow winding alleys instead of the recent four-lane straight roads, this effect might have been even stronger. This phenomenon, indicated by a mirror effect visible on photographs of inundated areas, has significant consequences for the discharge estimation as the dense settled areas of the floodplain might be left out as the water there is standing but not moving. Note, that this important observation requires further confirmation but so far provides significant ease as high resolution topographic data from within medieval cities would be hard to determine.

As the reconstruction of the geometry of historic river channels is already a challenge, the even more detailed determination of their roughness elements and the degree of their development appears rather doubtful. The question for existence and dimensions of mobile bedforms like gravel dunes or water plants illustrates the problem. On the other hand, the reconstruction of historic floods typically has to do with large scale high magnitude events of considerable water depth. Especially the significantly increased depth of flow in relation to mean flow conditions and its characteristic expansion of the entire floodplain obviously reduce the significance of the uncertain about these relatively minor roughness elements.

The open floodplain near historic locations like cities or monasteries with localised flood level information typically was used for agriculture. Even though knowledge on plants, techniques and methods of historic agriculture is well developed, a high resolution picture on which kind of plant of which size and leaf development exactly where was growing at the point of time of the flood occurrence cannot be determined. Based on the season the flood occurred, a more general picture of dense or vice versa missing agricultural vegetation cover with characteristic roughness value ranges can be plausibly quantified. Parts of the floodplain might have remained forested with uncertainties about species and densities like for the areas of agricultural use. Barnes (1967) documented photographic evidence of the appearance of floodplain forests with measured roughness values that might ease estimations for historic environmental conditions at least for a plausible magnitude of n-values. Even though the floodplain channels might still be delimitable in the recent urban topography (e.g. http://www.hw-karten.de/koeln/ for the example of Cologne) their historic appearance is not documented. Within the agriculturally used floodplain the incised and due to close groundwater contact rather wet channels were just disturbing and not worth to mention further on. From the recent topography, minimum values of their dimension is passed down though steeper slopes grown over with bushes and relatively dense vegetation cover tolerant to wet grounds are a picture of imagination only (cf. Herget and Meurs 2010). Considering expanded floodplains of such uncertain characteristics like characterized above with spread roughness value ranges explains that the approach presented here will always result in flood discharge ranges and not distinct values whatever future improvements on the approach will look like.

2.5 Validation and plausibility check

Validation of the estimated discharge data is possible by the application of the method on recent flood events and comparison of the estimation with gauge data. Table 1 presents mainly unpublished data based on flood reconstruction along the Rivers Rhine and Ahr, a minor tributary upstream from Bonn. Note, that no improvements of the flood discharge estimations were carried out by adaptation of n-values to narrow the differences with measured discharges.

Even though the comparisons documented in Tab. 1 are not representative, a tendency of underestimation of flood discharge for Q_p values is obvious. Typically, Q_p-estimations are up to 10% less than the related gauge data, while floods modelled in the low level gentle slope regions of the Lower Rhine at Düsseldorf and Rees differ even more. Discharge measurements of recent floods with water levels very far beyond bankfull inundating a broad differently structured floodplain are also less certain due to limited possibilities for gauge calibrations (e.g. Morgenschweis 2011).

An additional approach for plausibility test is the repeated reconstruction of flood discharges along rivers at different location and check consistency like increasing discharge downstream of confluences with major tributaries or relation to reliable locations for the same event (e.g. Elleder et al. 2013).

3 Conclusions

Based on sufficient historic background data like water level and previous topography, the approach is suitable to estimate the discharge of historic flood events with an accuracy of approximately ±10%. Application of the approach on recent floods and comparison with gauge data indicate a tendency of underestimation of the discharge based on data available so far. Doubtful data like contradictory handed down flood levels and uncertainties about the influence of destroyed bridges probably filling the river channel (e.g. Herget et al. 2014) can be handled by modelling different scenarios and subsequent plausibility checks of the estimated discharge data with additional locations up- and downstream the river. Additional sources of error are less significant than one might expect as high water levels over broadly inundated floodplains compensate less distinct values of the river channel morphology, historic accumulation level of floodplain sediments respectively extrapolated incision and accumulation rates. Rather time-consuming is the research for historic data on river channel conditions, high resolution historic topography and data of annual incision respectively accumulation rates of the river channel and floodplain in historic times.

The model itself is rather basic, considering simplified current pattern of one-dimensional steady flow that are far below real flow pattern of a passing-through floodwave. Two- or three-dimensional models for unsteady flow obviously would be more realistic, but usually cannot be fed with sufficient high resolution input data based on evidence from historic times. Some exceptions (e.g. Bürger et al. 2006, Calanda et al. 2003) proof this rule and might be considered or scientific and methodological interest rather than applied flood hazard assessment. Note, that not automatically an increase model complexity leads to an improved result, neither by spatial resolution nor accuracy but are much more complicated to handle (Carling et al. 2003).

Further improvement and development of the approach might be given by handling with flood flow current passing through settled areas. High resolution data on the detailed structure at the point of time of a specific flood event is as challenging as the flow itself. Either high-resolution modelling could be a perspective or the estimation of hydraulic roughness n-values for settled areas.

Author contributions

T.R. and M.K. carried out local studies along the Rivers Ahr and Rhine (T.R.) and Rhine and Main (M.K.) that are partly unpublished so far. J.H. prepared the manuscript based on their materials and previous own and other publications while the finally submitted manuscript was checked by all co-authors.

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Table 1: Comparison chart on estimated and measured peak discharges of selected flood events (partly from Meurs 2006 and Roggenkamp 2012)

Flood event	**River / city**	**Estimated peak discharge [m³/s]**			**Gauge data [m³/s]**	**Difference Q_p to Q_{gauge}**
		Q_{min}	Q_p	Q_{max}	Q_{gauge}	
Nov. 1882	Rhine / Andernach	8970	9785	10762	10700	-9%
Nov. 1882	Rhine / Düsseldorf	7391	8648	10549	10400	-17%
Nov. 1882	Rhine/ Rees	6047	7326	9422	10200	-28%
Jan. 1883	Rhine / Mainz	4455	5060	5860	6940	-27%
Jan. 1883	Rhine / Andernach	8317	9073	9980	< 9530	-5%
Jan. 1883	Rhine / Düsseldorf	6965	8142	9915	9710	-16%
Jan. 1883	Rhine / Rees	6200	7518	9676	10500	-28%
Apr. 1983	Rhine / Cologne	7800	9100	10200	9486	-4%
May 1983	Rhine / Cologne	7950	9300	10400	9724	-4%
Mar. 1988	Rhine / Cologne	7950	9300	10400	9708	-4%
Dec. 1993	Rhein / Cologne	8750	10250	11450	10836	-5%
Jan. 1995	Rhine / Cologne	8900	10450	11650	10939	-4%
Jan. 2003	Rhine / Cologne	7650	8950	10000	9329	-4%
May 1984	Ahr / Altenahr	148	182	232	192	-5%
Mar. 1988	Ahr / Altenahr	143	176	225	190	-7%

Figure 1. Flood marks of the River Main on the historic city fortification of Eibelstädt near Würzburg.

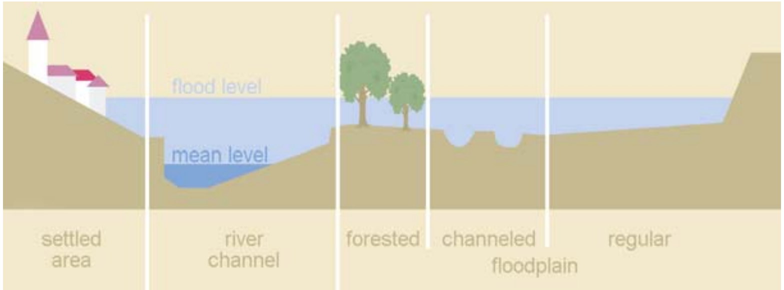

Figure 2. Scheme of homogenous units of floodplains with different hydraulic roughness characteristics (modified from Herget 2012).

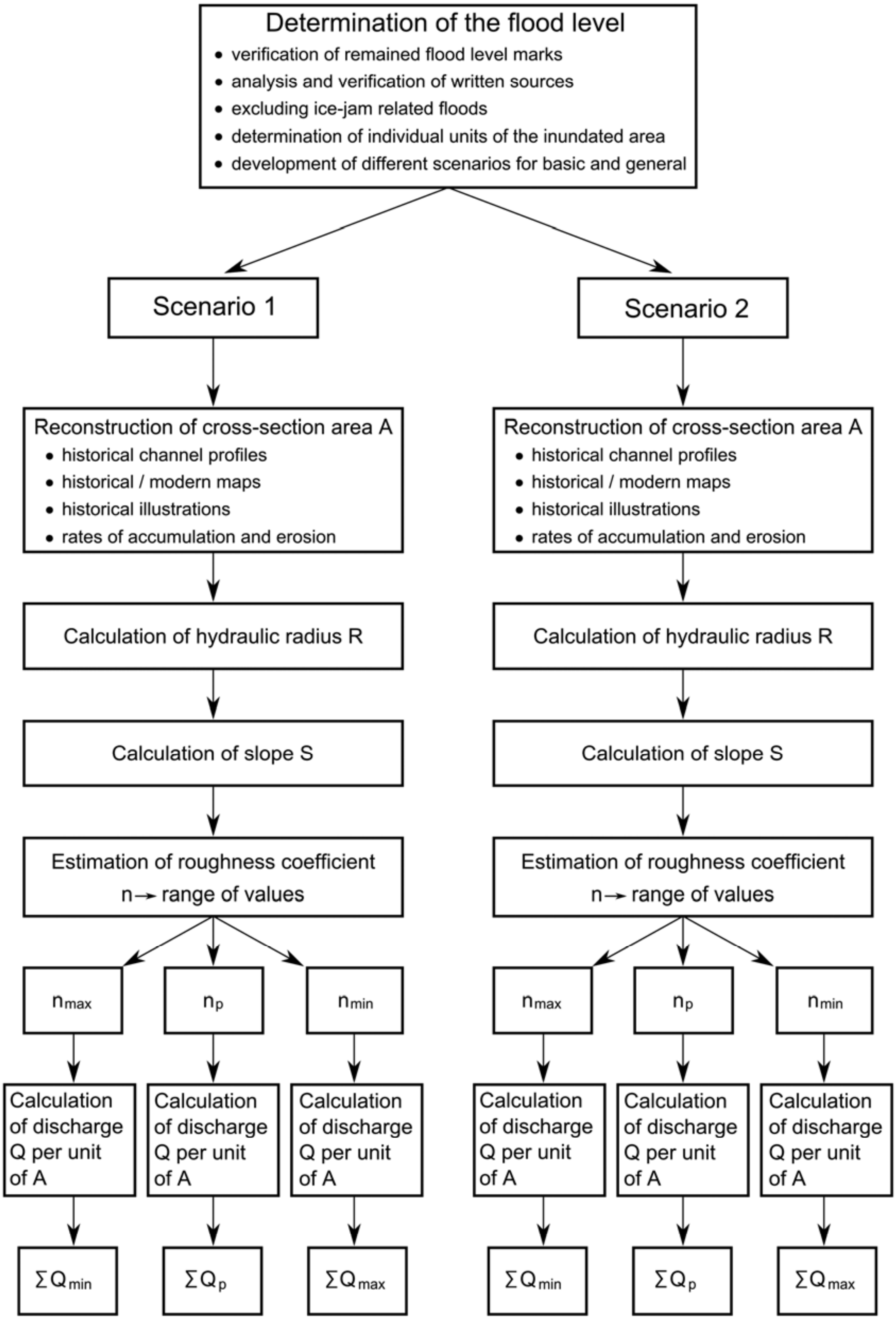

Figure 3. Scheme of discharge calculation and main aspects of parameter quantification