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The relationship between annual varve thickness and maximum annual discharge (1909–1971)

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Abstract

Annually laminated (varved) sediments from the River Ångermanälven, mid-central Sweden, have been used to construct an annual 2000-year long record of varve thickness. Maximum daily annual discharge and mean varve thickness for the years 1909–1971 are significantly correlated ($r = 0.87$). A relationship between maximum daily annual discharge for the observed period (1909–1971) and varve thickness was determined. The return time of two exceptionally thick varves in the 2000-year long record at the years 658 and 492 AD were estimated and their likelihood estimated based on a Gumbel frequency analysis.

Keywords: Maximum daily annual discharge; Varve thickness; River Ångermanälven; Mid-central Sweden; Quantitative flood reconstruction; Gumbel; 2000-Year record

1. Introduction

Varved sediments are deposits with distinct annual layers, which form under anaerobic conditions in lakes, marine environments and river estuaries. Their importance and potential for annual to centennial reconstructions of past environmental and climatic changes have during the last decade been demonstrated in a number of studies. Varved records from high arctic and alpine lakes have, e.g. been used as a tool for assessing past discharge, precipitation and/or temperature variations on annual to decadal time scales (Desloges, 1994; Gajewski et al., 1997; Hardy et al., 1996; Hughen et al., 1996, 2000; Lamoureux and Bradley, 1996; Leemann and Niessen, 1994). Clastic varved sediments are frequent in many river estuaries in northern and mid-central Sweden, where they are composed of distinct sand/silt and clay couplets (Cato, 1987; Widerlund and Roos, 1994) and potentially form a valuable archive for reconstructing past discharge variations.

The major part of the sediment load in non-regulated rivers in northern Sweden is transported during the yearly snowmelt flood, which occurs in May and June (Brandt, 1990). The relationship between increased discharge during the snowmelt flood and annual varve thickness was recognized by Kullenberg

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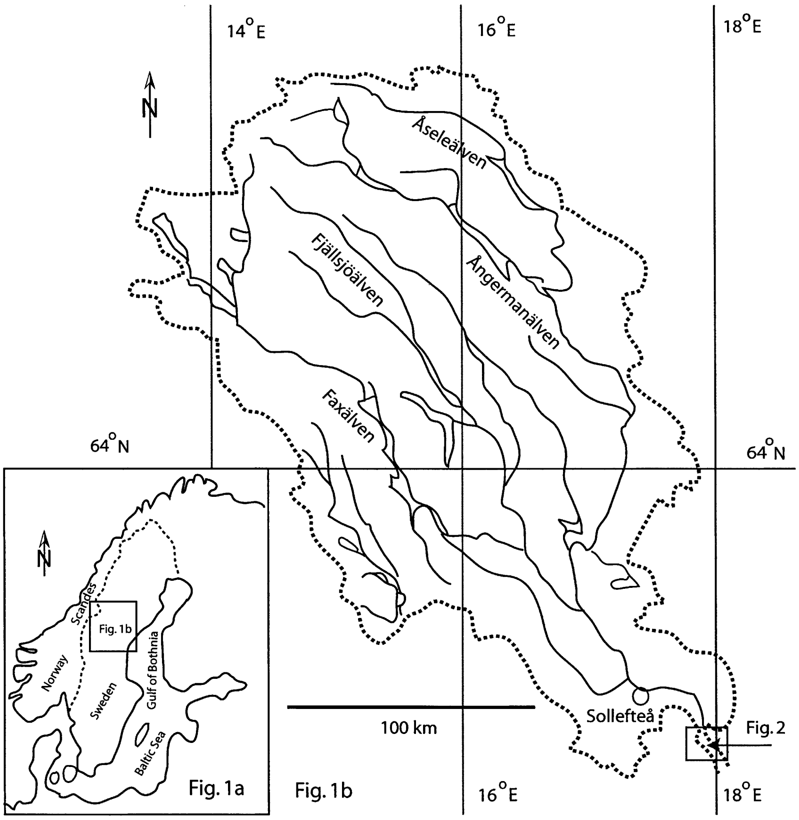

Fig. 1. Map of Scandinavia (a) and the catchment of River Ångermanälven (b). The stippled line in (b) shows the catchment boundary.

Table 1
Correlation of individual varve thickness sequences from River Ångermanälven to Q_{max} according to Cato (1987). The relationship follows the equation $Q_{max} = a' + b' \ln(vt)$. vt = varve thickness, Q_{max} = maximum daily annual discharge; a' and b' are transformed values of a ($a' = -(1/b) \ln a$) and b ($b' = 1/b$) in Cato's (1987) exponential equation; n = number of varves; r = correlation coefficient; PC = piston core, GC = gravity core. See Fig. 2 for the location of the cores in the estuary

Core number	Years covered	n	r	a'	b'
PC 2	1909–1919	11	0.65	1051	476
PC 3	1909–1935	27	0.68	342	416
PC 6	1909–1919	11	0.80	1063	400
GC 2	1927–1971	45	0.52	353	555
GC 3	1944–1973	30	0.57	444	435
GC 8	1940–1972	33	0.63	255	500
GC 9	1922–1957	35	0.80	269	625
GC 491	1949–1978	29	0.50	177	475

and Fromm, (1944), who attributed the exceptionally thick varve in 1927 in cores from the River Ångermanälven estuary (Fig. 1a and b) to the unusually powerful snowmelt flood of that year. The first scatter plot of maximum daily annual discharge (i.e. the average of observations during the day of highest discharge, here after Q_{max}) and varve thickness measurements with a proposed model was published by Granar (1956), also based on sediments from River Ångermanälven. However, the relationship was not explicitly expressed. In 1987, Cato (1987) presented multiple sediment cores with annually laminated, varved clays and silts from the River Ångermanälven estuary. By measuring varve thickness variations along each core and by the successive correlation of overlapping cores, he was able to construct an absolute annual timescale reaching back to 550 BC. To show that each of the clay/silt couplets represents 1 year, he compared annual varve thickness in single cores to

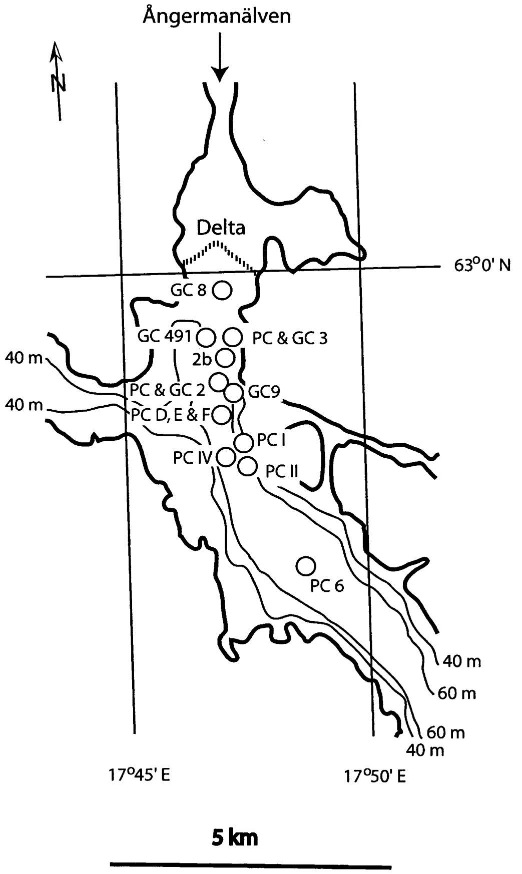

Fig. 2. The location of the 15 sediment cores in the River Ångermanälven estuary (Cato, 1987). See Table 2 for details on the individual cores.

Q_{max} records for the years 1909–1978 (Table 1). His results showed that the correlation between maximum daily annual discharge and annual varve thickness follows the exponential equation $\mathrm{vt} = a\,\mathrm{e}^{bQ_{max}}$, which is here rewritten for comparisons to the present study as (Eq. (1))

$$Q_{max} = -(1/b)\ln a + (1/b)\ln(\mathrm{vt}) \rightarrow Q_{max} = a' + b' \ln(\mathrm{vt}) \quad (1)$$

where vt is the varve thickness (cm), a and b are constants and Q_{max} is maximum daily annual discharge ($m^3\,s^{-1}$).

The correlation coefficients *(r)* reported by Cato (1987) vary from core to core and range between +0.50 and +0.80 (Table 1). This range is caused by local variations in varve thickness within the delta both in space and time. Varve thickness generally decreases from the proximal to the distal parts of the delta and total sediment transport changes from year to year as a response to the intensity of the flow. Therefore, a different approach was attempted by Wohlfarth et al. (1998), who first validated the youngest part of Cato's (1987) varve correlations statistically and then correlated a geometric mean time series of varve thickness to mean monthly discharge variations between 1909 and 1950. Significant correlations were only found for May ($r = 0.49$), June ($r = 0.70$) and July ($r = 0.35$).

None of the correlation attempts cited above, which have been used to describe the functional relationship between annual or mean varve thickness and discharge variations, can be regarded as sufficient because: (1) varve thickness/discharge correlations and regressions were performed on single sediment sequences only (Cato, 1987), and therefore, do not account for spatial variations in varve thickness; (2) the major part of the varve thickness is related to the period of maximum daily annual discharge, and the mean monthly values used in the study by Wohlfarth et al. (1998) smooth out or reduce the contribution of Q_{max}, which is known to be an important control.

In the present study, varve thickness measurements on 15 sediment cores from the River Ångermanälven estuary (Figs. 1 and 2, Table 2) covering the time period 1909–1971 are used to find a reliable equation, which adequately expresses the relationship between varve thickness and Q_{max}. This equation is then used to reconstruct maximum daily annual discharge variations for the past two millennia, based upon Cato's (1987) 2000-year long varve record. The approach represents the first quantitative assessment of maximum daily annual discharge variations over a 2000-year long interval.

2. The River Ångermanälven catchment and estuary

River Ångermanälven is located in mid-central Sweden (Fig. 1a). It originates in the Scandes Mountains and discharges into the Gulf of Bothnia of the Baltic Sea. The river consists of the three main tributaries, Åseleälven/Ångermanälven, Fjällsjöälven and

Table 2
Varve sequences covering the 1909–1971 period compiled for this study and the water depth in which the cores were retrieved, distance to the present delta and the time span covered by each sequence. See Fig. 2 for location of the cores

Core number	Reference	Depth (m)	Time span years (AD)
GC 491	Axelsson (1983)	42	1949–1978
GC 2	Cato (1987)	53	1927–1971
GC 3	Cato (1987)	47	1944–1973
GC 8	Cato (1987)	19	1940–1972
GC 9	Cato (1987)	75	1922–1957
PC I	Granar (1956)	95	1850–1933
PC II	Granar (1956)	95	1860–1923
PC IV	Granar (1956)	65	1850–1949
PC 2b	Kullenberg and Fromm (1944)	60	1926–1942
PC 2	Cato (1987)	53	952–1919
PC 3	Cato (1987)	47	1791–1935
PC 6	Cato (1987)	100	1200–1920
PC F	Unpublished	> 60	1414–1930
PC D	Unpublished	> 60	1494–1926
PC E	Unpublished	> 60	1414–1924

Faxälven. Åseleälven/Ångermanälven and Fjällsjöälven merge about 40 km upstream of the confluence with Faxälven at the town of Sollefteå (Fig. 1b).

The catchment covers ca. 30,000 km^2, of which 7% are lakes (SMHI, 1994) and can roughly be divided into three landscape zones. The Scandes Mountains to the west rise to 1200 m a.s.l., have mean annual temperatures around 2 °C and a mean annual precipitation of 600–1200 mm. The central part is a highland area with altitudes between 500 and 1000 m, mean annual temperatures between 0 and 4 °C and a mean annual precipitation of around 500 mm. The coastal zone to the east has a mean annual temperature slightly above 4 °C and an annual average precipitation of 600–700 mm.

The river's estuary is ca. 2–3 km wide and about 50 km long. Its depth beyond the delta crest ranges between 15 and 120 m below sea-level. Resuspension generated by wave action is, therefore, comparably small. The estuary has no tidal influence. Several delta lobes are present in the active delta and in the inactive, erosive, uplifted area behind the delta front. Sedimentation occurs mainly in the western part of the present delta, which is separated from the eastern part by a shallow central channel. The delta crest surface lies at a depth of 0–1.5 m below sea-level and average sediment thickness in the estuary is estimated at 50–100 m (Arnborg, 1959). The active delta is built up of river transported sand and silt (Arnborg, 1959). The narrow estuary is influenced by an isostatic rebound of 0.85 mm/year (Bergsten, 1954), which progressively forces the younger sediments to be deposited further outward to the south.

After the construction of the first hydro-electrical power station in 1939, 40 additional power plants have been built along River Ångermanälven and its tributaries. The impact of these constructions, from around 1950 and onwards, can be clearly seen in the river's discharge distribution, which has become rather uniform. Between 1909 and 1950, the maximum daily annual discharge ranged between 1102 and 3262 m^3 s^{-1}, but declined to 553–1956 m^3 s^{-1} between 1951 and 1971. Average $Q_{\max}$ during the years 1909–1950 was 1922 m^3 s^{-1}, but decreased to 1180 m^3 s^{-1} during the period 1951–1971. The changes due to regulation are most significant for May and June, where monthly river flow is reduced by about 500 m^3 s^{-1}, while it is increased by a few hundred m^3 s^{-1} during the remaining months. Before the river was regulated, maximum monthly discharge always occurred during May or June except for 1921 when the maximum monthly discharge occurred in August. In the regulated river, water is withheld for later release during winter, when the natural runoff is low. Although the annual peak flow still frequently occurs in May and June, in some years it may, therefore, occur during other months.

3. Discharge peaks

The yearly snowmelt floods during spring in northern and mid-central Sweden are considerable higher than the flow during the rest of the year. Due to leakage of groundwater winter discharge for the preregulation period is around 100–200 $m^3 s^{-1}$, but discharge increases to 2000 $m^3 s^{-1}$ on average during snowmelt. In the preregulation period only 1 year experienced monthly maximum discharge outside the snowmelt period. Since the catchment is large, increased flows are likely to persist for several days. During winter, the solid precipitation does not generate runoff, and river discharge declines.

The snowmelt is generally distributed over 1–2 months, depending on how homogenous the river basin is, and starts in the downstream parts of the basin. In open areas, snow disappears over a period of 2–3 weeks, while it lasts usually 1–2 weeks longer in forested areas. Snow in the downstream lowland often disappears before the snow in the mountains begins to melt. However, in years with a late spring, melt may occur at the same time in the lowlands and in the mountains, which results in extreme flows. The precipitation as rain during summer and autumn equals approximately the snow precipitation during winter and spring, but due to evaporation, less runoff is generated. Prolonged rain during summer and autumn can also produce significant peaks comparable to that of the snowmelt flood (SMHI, 1994)

Basically, six factors influence the magnitude of the snowmelt flood: (1) the amount of snow accumulated during winter; (2) the melt rate, which is determined mainly by air temperature and solar radiation; (3) the distribution of the melt over the river basin; a synchronous melt over the whole basin results in very high river flows; (4) available soil moisture storage; thick soils of low soil moisture content can store much water and release water to the ground water slowly, thus delaying runoff and reducing the peak flows. However, during prolonged snowmelt, the soils reach field capacity and in the last phase of the snow melt period most melt water recharges the groundwater without increasing the soil moisture or runs off as saturated overland flow or as hortonian flow; (5) soil frost; in forests the soil frost does not influence the soil moisture process and the groundwater recharge; however, in open fields with clay-rich soils and a less developed macro-pore structure, the initial melt water first moves into cracks in the soil, and when these cracks become clogged with ice, the melt water moves as overland flow; (6) lakes; water is temporarily stored in lakes and the flow is attenuated. However, if the lakes are small and the high flow continues over a longer period, the attenuation effect is minor.

Extreme flows are often of short duration and their magnitude is not always well represented in monthly average values. In 1920, the maximum daily annual discharge was 2895 $m^3 s^{-1}$, whereas the monthly discharge for June only reached 1573 $m^3 s^{-1}$. In contrast, the difference between maximum daily annual discharge and mean monthly discharge for June 1939 was only 50 $m^3 s^{-1}$.

In a number of empirical studies annual, monthly or maximum daily annual discharge values have previously been used to explain varve thickness variations (Cato, 1987; Gilbert, 1975; Widerlund and Roos, 1994; Wohlfarth et al., 1998). However, there are numerous theoretical formulas for estimating the sediment load (Q_{sed}) in rivers. They may be based on the tractive force concept such as duBoys classical formula, on the concept of fluid turbulence and boundary layer as Einstein's formula or on energy relations, as the approach by Bagnold (1966). The suspended load, usually much less than the bed load, is, except in the approach by Bagnold, from which the total sediment load is computed directly, indirectly estimated from the bed load. All formulas give the sediment load as a function of river discharge per unit width, depth, bed slope and grain size. A friction formula can be used to relate discharge and water depth. When doing so, as was done by, for example, Raudkivi (1967), the sediment load, (Q_{sed}), is proportional to the river discharge Q raised to an exponent, which for the most commonly used formulas is about 2. River bank erosion is mainly attributed to the rising limb of the flow and wash-load of fine material from close-by soils to the first occasion when water moves as overland flow. There is probably only a limited amount of material to be transported during the recession of the flow, following snowmelt or a large storm. It is, therefore, justifiable to attribute the majority of the sediment transport to discharge occurring during the short snowmelt floods (Brandt, 1982). Since the catchment is large, maximum daily annual discharge is a reasonable proxy for discharge during a few days.

Table 3
Correlation coefficients between mean annual varve thickness and Q_{max} calculated for the pre- and post-regulation period

Period	r
1909–1950	0.87
1950–1971	0.88
1909–1971	0.87

4. Materials

The varve thickness data set used here has been presented in Cato (1987) and constitutes a continuous annual sediment record for the years 1978 AD to 28 BC. The sediment cores were obtained in different parts of the estuary, all beyond the present delta crest (Fig. 2, Table 2). The visual correlations between single varve thickness diagrams (Cato, 1987) were confirmed by statistical cross-correlation analyses (Wohlfarth et al., 1998) (Holmquist, unpublished). The down-core compaction of the sediments was accounted for by eliminating the exponentially decreasing down-core trend and a geometric mean of the overlapping varve series was then calculated.

To evaluate the best fitting equation between Q_{max} and mean annual varve thickness, 15 sequences, which cover the time period 1909–1971, were selected (Table 2). This period was chosen because a record of maximum daily annual discharge is available since 1909 and because the few varve sequences, which cover the years 1972–1978, are not considered sufficient for calculating a representative mean. The reconstruction of Q_{max} on a longer time scale is based on the geometric mean of the 1971 AD to 28 BC data set.

Maximum daily annual discharge data were compiled from the hydrological station at Sollefteå (Fig. 1b), where discharge measurements began in 1909 and have since continued uninterrupted (SMHI, 1994).

5. Results

5.1. Varve thickness–Q_{max} relationship

The extensive regulation of the river for hydroelectrical purpose has changed the yearly flow and created artificial sediment traps in numerous reservoirs, which potentially alter the relationship between varve thickness and Q_{max}. However, the correlation coefficients calculated for the regulated ($r = 0.88$) and unregulated ($r = 0.87$) period show that the regulation did not affect the varve–Q_{max} relationship (Table 3), although maximum daily annual discharge and varve thickness decrease distinctly after the major dam constructions in the early 1950s (Fig. 3). The

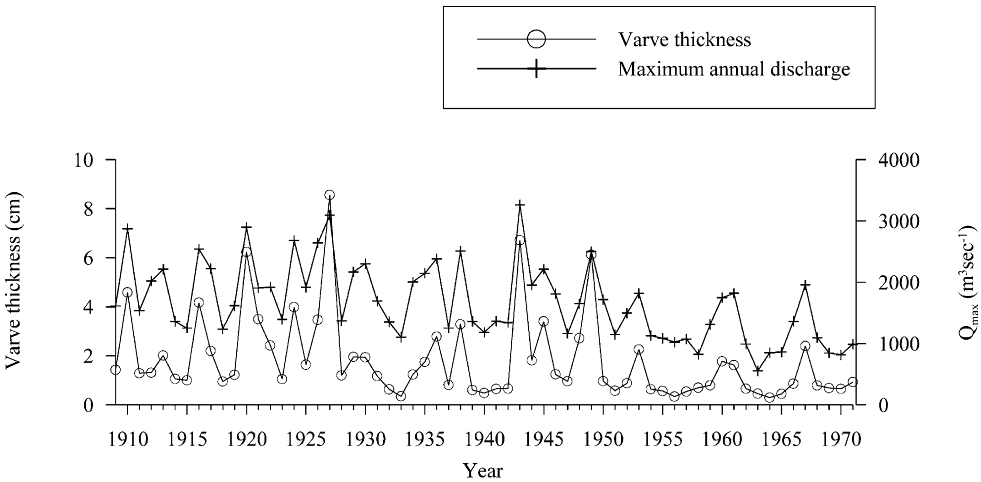

Fig. 3. Varve thickness (cm) (open circles) and Q_{max} ($m^3 s^{-1}$) (crosses) variations from River Ångermanälven between 1909 and 1971 (Cato, 1987; SMHI, 1994) shown on a common annual time scale. See Fig. 2 for the location of the individual sediment cores and Table 3 for the correlation coefficients between Q_{max} and varve thickness.

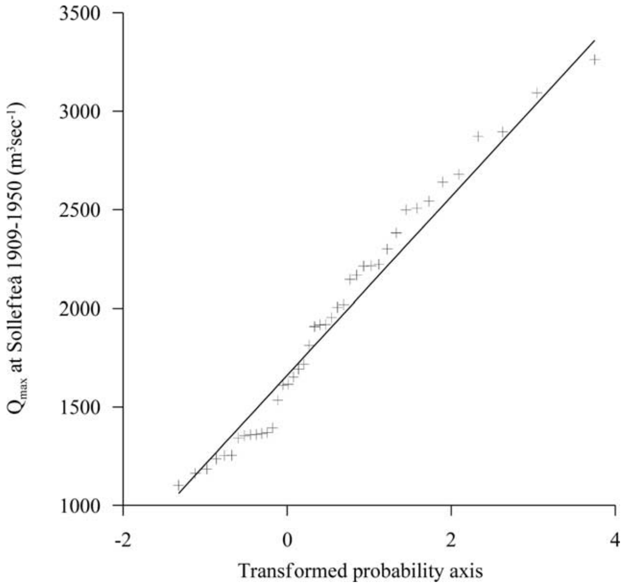

Fig. 4. Gumbel frequency analysis of Q_{max} between 1909 and 1950.

strong relationship between varve thickness and Q_{max} before and after the regulation justifies the use of the entire1909–1971 period for fitting different equations.

The Gumbel frequency analysis shows that unregulated Q_{max} follows the Gumbel distribution well (Fig. 4). The maximum flood of the 1909–1950 period occurred in 1943 and has a return time of ~30 years. A slightly longer return time would be expected

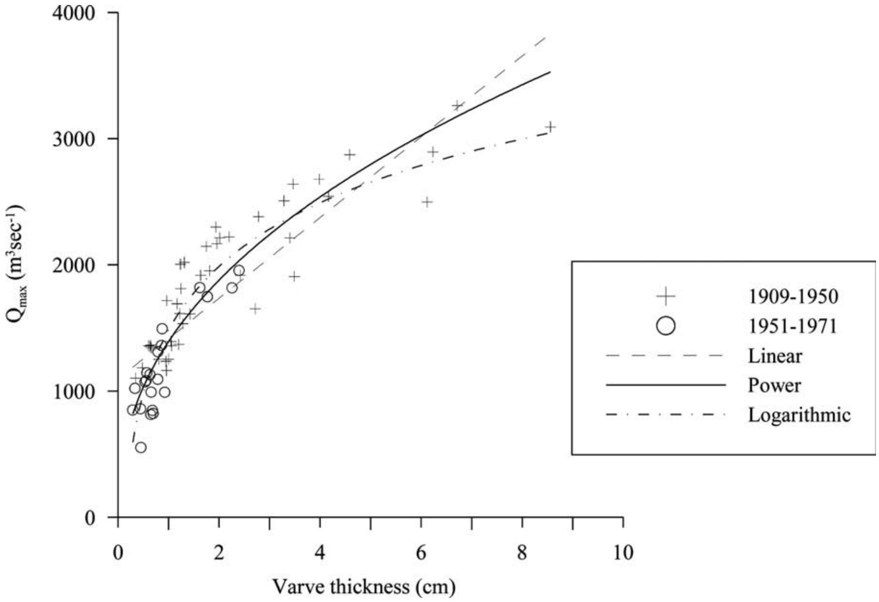

Fig. 5. Scatter plot of varve thickness (cm) versus Q_{max} ($m^3\ s^{-1}$) for the 1909–1971 period. Q_{max} for the regulated period is shown by open circles and for the unregulated period by crosses. The three equations, linear (thin black line), power (thick black line) and logarithmic (dotted line) are fitted by a least sum of squares to the data set.

Table 4
Bootstrap results, showing the calculated values of a and b for the 1909–1971 data series. Central values and the 95% confidence levels of a and b are shown. Q_{max} = maximum daily annual discharge ($m^3\ s^{-1}$), a and b = constants, vt = varve thickness (cm). a' and b' are the constants reported by Cato (1987), which were here recalculated for comparison to this study's logarithmic equation. See Table 1 for details

Equation		a	b	a'	b'
Linear $Q_{max} = a + b\text{vt}$	2.5%	974	233	1051	476
	Central	1093	320	342	416
	97.5%	1195	380	1063	400
Logarithmic	2.5%	1417	641	444	435
$Q_{max} = a + b\ \ln(\text{vt})$	Central	1485	729	255	500
	97.5%	1549	809	269	625
Power $Q_{max} = a\text{vt}b$	2.5%	1314	0.38		
	Central	1392	0.43		
	97.5%	1452	0.49		

because the highest flood of a Q_{max} record normally has a return time which is slightly longer than the number of observation years.

5.2. Model description and validation

In the scatter plot (Fig. 5), varve thickness is plotted against Q_{max} for the years 1909–1971. Three different regressions are fitted by means of sum of least squares, i.e. linear (Eq. (2)), logarithmic (Eq. (3)) and power function (Eq. (4)).

$$Q_{max} = a + b\text{vt} \tag{2}$$

$$Q_{max} = a + b\ \ln(\text{vt}) \tag{3}$$

Table 6
Mean and standard deviation and Gumbel parameters for Q_{max} during the unregulated period (1909–1950) and for the 40 successive maximum from the 2000 years of reconstructed Q_{max}. $\alpha = \text{Std}(Q)/1.28$ and $\beta = \text{Mean}(Q) - 0.45\text{Std}(Q)$. The 1000, 2000 and 10,000-year floods have been calculated anticipating a Gumbel distribution (1909–1950) with the properties listed

	1909–1950	28 BC–1971AD 50 years maxima
Mean (Q_{max})	1922	1441 $m^3\ s^{-1}$
Std (Q_{max})	580	474 $m^3\ s^{-1}$
α	453	371
β	1661	1228
1000 year	4790 $m^3\ s^{-1}$	
2000 year	5104 $m^3\ s^{-1}$	
10,000 year	5833 $m^3\ s^{-1}$	

$$Q_{max} = a\text{vt}^b \tag{4}$$

where Q_{max} is the maximum daily annual discharge ($m^3\ s^{-1}$), vt the varve thickness (cm), a and b are constants.

In order to validate and discriminate between the three models and to obtain values of a and b, a bootstrap method was applied (Table 4). From the whole data set, 15,000 samples containing 40 data points were randomly extracted, a regression was fitted to each sample and the 95% confidence intervals were calculated for a and b. Bootstrap on the linear regression yields asymmetrical residuals, i.e. randomly taken samples are prone to yield two populations of regressions with significantly deviating values of a and b. The logarithmic and the power functions yield symmetric residuals. The distribution of the data set shows that the linear equation (Eq. (2)) does not allow describing the full range of data, while both

Table 5
Reconstructed Q_{max} for the two thickest varve in the 2000-year long varve series and their return time. The values of a and b for the respective equations (Eqs. (2)–(4)) are derived from the central values in Table 2. The return time is calculated expecting a Gumbel distribution with the properties of Q_{max} for the 1909–1950 period (see Table 6)

	Power	Logarithmic	Linear
492 AD	4609 $m^3\ s^{-1}$	3498 $m^3\ s^{-1}$	6179 $m^3\ s^{-1}$
Approximate return time	670 years	60 years	21,500 years
658 AD	5827 $m^3\ s^{-1}$	3892 $m^3\ s^{-1}$	9827 $m^3\ s^{-1}$
Approximate return time	9900 years	140 years	67 million years

Table 7
Calibration and validation results, based on the power equation; a and b are constants derived from a regression calculation for the 1909–1940 period and are subsequently used to calculate Q_{max} for the following period (1941–1971). r^2 for the calibration period and validation period, respectively, are given

Calibration 1909–1940	$a = 0.37$ $b = 1523$ $r^2 = 0.85$
Validation 1940–1971	$r^2 = 0.85$

the logarithmic (Eq. (3)) and the power (Eq. (4)) equations result in good fits (Fig. 5).

To further evaluate the three equations, maximum daily annual discharge for two exceptionally thick varves (658 AD: 27.3 cm and 492 AD: 15.9 cm) from the 2000-year long record were used to reconstruct maximum daily annual discharge by using the central values of a and b obtained from the bootstrap (Table 4). The return time of the extreme events was calculated by assuming a Gumbel distribution with the properties shown in Table 6. The linear model gives Q_{max} values of 9800 and 6200 $m^3\ s^{-1}$ and a return time of 67 million and 21,500 years, respectively (Table 5). The logarithmic model, on the other hand, yields Q_{max} values of 3800 and 3500 $m^3\ s^{-1}$ and a return time of the floods of 140 and 60 years. The power model seems to give the most realistic values with a Q_{max} of 5800 and 4600 $m^3\ s^{-1}$, respectively, and a corresponding return time of 9900 and 670 years.

Q_{max} derived from the linear model over-estimates the expected values, while the logarithmic model gives significantly lower Q_{max} than what would be expected based on the observed maximum daily annual discharge record. In contrast to the power equation, the logarithmic equation does not yield a substantial increase in Q_{max} coincident with an increase in varve thickness which implies that modest discharge changes bring about substantial changes in sediment transport when Q_{max} exceeds ~2500 $m^3\ s^{-1}$ (Fig. 5). Therefore, the logarithmic equation cannot be regarded as adequate to reconstruct Q_{max} from varve thickness. Furthermore, there are also physical reasons for a power relationship between sediment transport (varve thickness) and flow velocity (discharge). Erosion is proportional to the square of the flow velocity and transport of suspended material is proportional to the velocity. The sediment transport thus adds up to be proportional to the flow of the velocity to the power of three.

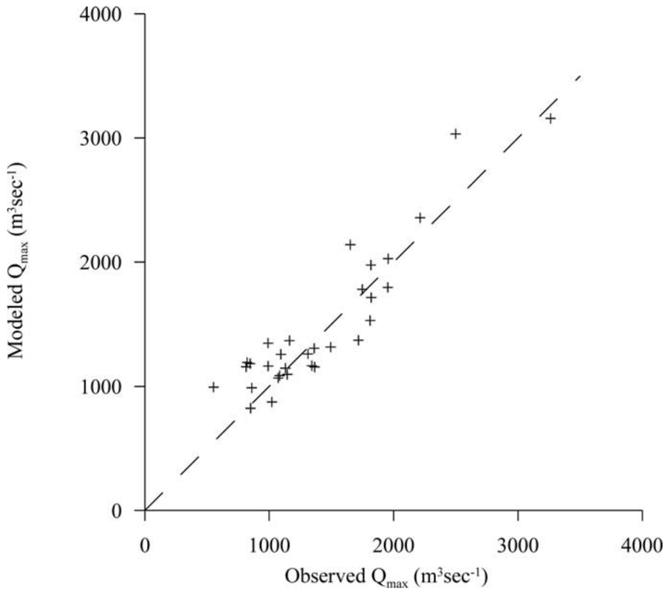

Fig. 6. Observed Q_{max} plotted against modeled Q_{max} for the 1941–1971 period, based on the power equation. The dashed line represents a 1:1 relationship. See Table 7 for values of a, b and explained variance.

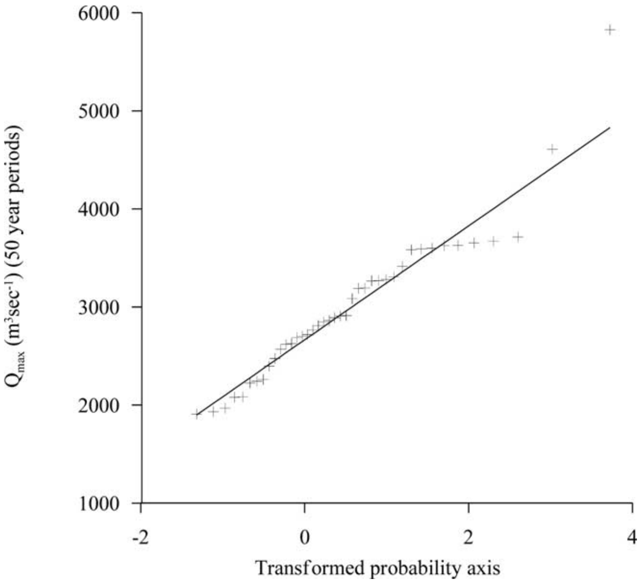

Fig. 7. Reconstructed Q_{max} values for successive 50 year periods between 28 BC and 1971 AD on a Gumbel distribution axis. The solid line represents the theoretical Gumbel distribution for the reconstructed Q_{max} values.

To validate the proposed power relationship between varve thickness and maximum daily annual discharge, a power regression was calculated based on the 1909–1940 period (Table 7). The obtained values of a and b were then used to model Q_{max} for the 1941–1971 period, based on varve thickness variations, and to compare it with observed Q_{max} (Fig. 6). The modeled Q_{max} explains 85% of the variance of the observed Q_{max} series (Table 7). The validation successfully utilizes pre-regulation data to predict

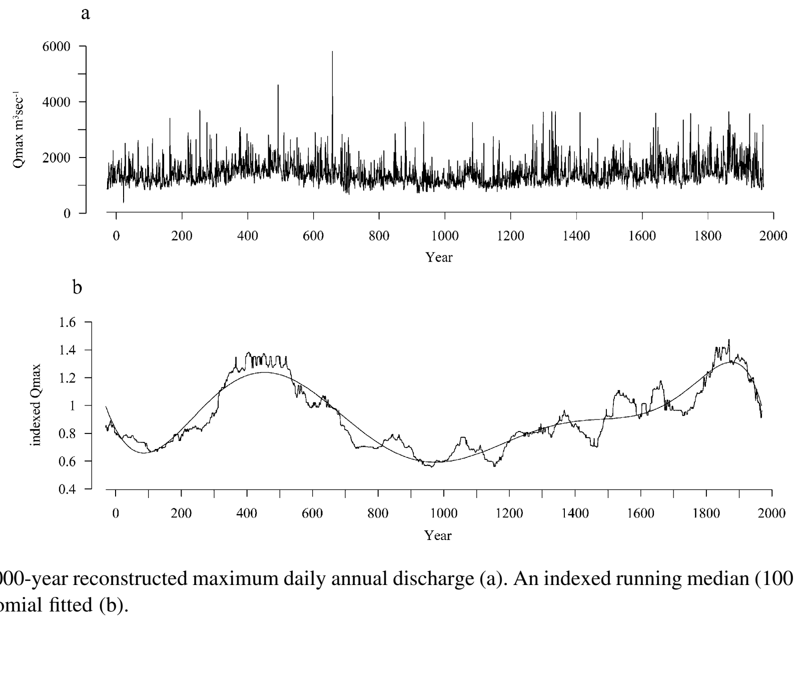

Fig. 8. Time-series of 2000-year reconstructed maximum daily annual discharge (a). An indexed running median (100 years) is shown in black with an 8 degree polynomial fitted (b).

pre- and post-regulation data, suggesting that the proposed power relationship is robust even when major interventions in the catchment occur.

6. Reconstruction and distribution of extreme Q_{max} on a 2000-year long time scale

On the basis of the 42 year-long data set (1909–1950) of observed unregulated maximum daily annual discharge at Sollefteå, the arbitrary chosen floods for the 1000, 2000 and the 10,000 return time were calculated by assuming a Gumbel distribution. The 1000 and 2000 year floods should be comparable with the two extreme floods reconstructed at 658 and 492 AD. The catchment of River Ångermanälven became ice free around 10,000 years ago. Hence, the maximum flood ever to have occurred in the river basin is expected to have a return time of around 10,000 years. The resulting Q_{max} values reach 4800, 5100 and 5900 $m^3 s^{-1}$, respectively (Table 6). As shown above, the linear model yielded a Q_{max} of 9800 $m^3 s^{-1}$ for the thick varve in the year 658 AD and of 6200 $m^3 s^{-1}$ for the varve in the year 492 AD (Table 5). The first value is twice the volume/second expected for the 10,000-year flood from the observed record and the latter value corresponds approximately to the 10,000 year return flood. Q_{max} derived from the logarithmic model yielded ~3900 and 3500 $m^3 s^{-1}$ for the two exceptionally thick varves, which corresponds to the 140 and 60 year return floods. This is considerably below the values expected based on the instrumental record. The power equation gives Q_{max} values of 4600 and 5800 $m^3 s^{-1}$ for the two thick varves, which is comparable to the 1000 and 10,000-year return floods calculated based on the instrumental record (Tables 5 and 6).

From the 2000-year long varve sequence, a maximum daily annual discharge time series was modeled using the suggested power equation. The obtained Q_{max} values were divided into forty 50-year long intervals and the maximum value of each interval was extracted and plotted on a Gumbel probability axis (Fig. 7). Reconstructed Q_{max} of less than 3600 $m^3 s^{-1}$ follows generally a Gumbel distribution. The plateau seen at around 3600–3700 $m^3 s^{-1}$ is either related to a certain threshold for the height of Q_{max} in the river or, to a climatic signal, which causes centennial periodicities in the varve record (Sander, in preparation). The second highest discharge peak (492 AD) appears to be of the right height as compared to the theoretical Gumbel distribution. The highest discharge peak (658 AD) has a return time, longer than what is covered by the 2000-year record and has, as shown above, the magnitude of the ~10,000 year flood.

It is not unequivocal to compare the Gumbel frequency distribution of reconstructed with observed maximum daily annual discharge by simple scale calculations (Table 6). A pre-requisite for such a comparison would be that Q_{max} derived from varve thickness is independent. Modeled maximum daily annual discharge (Fig. 8) shows considerable variations during the past 2000 years. High values are persistent for the periods 300–650 and 1750–1971 AD and lower values for the periods 28 BC–300 AD and 650–1750 AD. These changes were likely related to climatic fluctuations and might be associated with known climatic excursions, i.e. the Medieval Warming Period (Hughes and Diaz, 1994) and the Little Ice Age (Bradley and Jones, 1993) (Sander, in preparation). Consequently, climatic factors must have influenced the distribution of maximum daily annual discharge on longer time scales.

7. Conclusions

This study presents an evaluation of the best fitting equation (linear, logarithmic, power) to describe the relationship between Q_{max} and mean annual varve thickness. The annually laminated, varved, sediment record is derived from the River Ångermanälven estuary in mid-central Sweden. Q_{max} and mean varve thickness for the years 1909–1971 are significantly correlated ($r = 0.87$), although the river was highly regulated in the 1950s.

For the period of observed Q_{max} (1909–1971), the data pool does not support a linear equation, whereas the logarithmic and the power equations fit well to the data. Reconstructed maximum daily annual discharge for two extreme events in the 2000-year long record (658 and 492 AD) resulted in 9827 and 6179 $m^3 s^{-1}$ for the linear equation, in 3892 and 3498 $m^3 s^{-1}$ for the logarithmic equation and in 5827 and 4609 $m^3 s^{-1}$

for the power equation. The return time of these reconstructed flood events is 67 million and 21,500 years (linear equation), 140 and 60 years (logarithmic equation) and 9900 and 670 years (power equation). The linear equation is thus overestimating extreme Q_{max} and the logarithmic equation under-estimates extreme Q_{max}. The two highest Q_{max} events derived from the power equation are comparable to the anticipated 1000 and 10,000 year floods, which supports the use of a power equation for reconstructing maximum daily annual discharge based on varve thickness.

The reconstructed maximum daily annual discharge maxima extracted from forty successive 50-year periods follow generally a Gumbel distribution. However, due to centennial periodicities inherent in the long varve thickness record (Sander, in preparation), which are likely related to past climatic changes, successive 50-year reconstructed Q_{max} maxima cannot be regarded as a scaling transformation of the observed yearly record.

The reconstructed Q_{max} values, based on the 2000-year long annual sediment record from River Ångermanälven, constitute the first annually resolved millennial long quantitative assessment of extreme floods.

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