No upward trends in the occurrence of extreme floods in central Europe

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Extreme river floods have been a substantial natural hazard in Europe over the past centuries[1], and radiative effects of recent anthropogenic changes in atmospheric composition are expected to cause climate changes, especially enhancement of the hydrological cycle[2], leading to an increased flood risk[3,4]. For the past few decades, however, observations from Europe[1,5–7] do not show a clear increase in flood occurrence rate. Here we present longer-term records of winter and summer floods in two of the largest rivers in central Europe, the Elbe and Oder rivers. For the past 80 to 150 yr, we find a decrease in winter flood occurrence in both rivers, while summer floods show no trend, consistent with trends in extreme precipitation occurrence. The reduction in winter flood occurrence can partly be attributed to fewer events of strong freezing—following such events, breaking river ice at the end of the winter may function as a water barrier and enhance floods severely. Additionally, we detect significant long-term changes in flood occurrence rates in the sixteenth to nineteenth centuries, and conclude that reductions in river length, construction of reservoirs and deforestation have had minor effects on flood frequency.

The middle Elbe (between Litoměřice and Magdeburg) and middle Oder (between Racibórz and before Kostrzyn) drain basins (respectively 95,000 km^2 and 54,000 km^2) that are under a continental, low-range mountainous climate (Sudeten Mountains, Bohemia, Erzgebirge and Beskids). Floods in hydrological summer (May to October) are caused by heavy rainfall, and in the winter also by thawing snow[8,9]. Breaking river ice may function as a barrier, enhancing winter floods severely[9].

Weikinn's sources[10] contain 23,160 documentary entries on hydrographic events in Europe up to 1850, with high coverage of Germany and neighbouring countries. Entries were checked and augmented using further sources (see Supplementary Information) on historical Elbe and Oder floods. Local events were excluded by requiring information[10] supportive of a regional extent, namely: (1) floods at other places on the river, (2) floods of tributaries at the same time, and (3) favourable meteorological conditions such as large rainfall before a flood. Stage values, available for Elbe floods at Dresden, Pillnitz and Meißen[11–13] and for the Oder at Krosno and other stations[8,14], facilitated construction of an impact-related magnitude scale. We restricted the number of magnitude classes to three (1, minor; 2, strong; 3, exceptionally strong), as in refs 1 and 15. This reduction of information is balanced by a gain in robustness of the constructed records: errors in judging the magnitude of a flood (by witnesses, source authors, Weikinn or us), have a minor influence when class bounds are wide. Likewise, uncertainties in the stage–runoff relations (see below) are less important than when more classes were used.

Although Weikinn aimed to compile original sources by witnesses, he also listed other, unverified references, and did not use historical source interpretation. Therefore, to assess the reliability of the constructed flood records (Supplementary Information), a comparison was made with CLIMDAT[16], a climate database of historically and critically reviewed documents. CLIMDAT focuses on central and eastern Germany, Poland and the Czech Republic, and covers the interval AD 1500 to 1799. For class-3 events, the agreement ("Weikinn's" floods (year, season, month) listed in CLIMDAT) is 100% (Elbe, Oder), for class-2 events 72% (Elbe) and 65% (Oder), and for class-1 events 39% (Elbe) and 29% (Oder). Floods listed in CLIMDAT but not by Weikinn are few (Elbe, 1.5%; Oder, 10%) and probably of minor magnitude. Thus, the information provided by Weikinn on heavy floods (classes 2–3) after ~1500 probably has few errors (for example, duplication of events caused by misrecording). This is confirmed by the agreement between flood occurrence rates (see below) calculated from the Weikinn sources and CLIMDAT, which are indistinguishable within the confidence bands. On the other hand, our records may not be homogenous before ~1500 and for class-1 floods. Therefore we restrict statistical analyses to heavy floods after 1500. This conservative approach does not imply that the class-1 records are useless; Weikinn may have had access to information that has now been lost.

The Elbe flood record was extended to the present using measurements from Dresden: monthly maximum water stage from 1850 to 1892 (ref. 17), and daily runoff from 1852 to 2002 (Global Runoff Data Centre (GRDC), http://www.wetteronline.de). The Dresden runoff time series exhibits excellent correlations with daily runoff series from Elbe stations Děčín (1887–1990, lag = 0, $r^2 = 0.98$) and Barby (1899–1999, lag = 2 days, $r^2 = 0.91$), which underline the regional character of the constructed record. Note that daily runoff was rarely measured directly but rather inferred via stage by frequently updated stage–runoff relations, introducing uncertainty. For Dresden this relation was found[18] to have changed only slowly over time, and to be valid also for upper values. For the interval 1852–92, this assessment is supported (Fig. 1a) by the high correlation ($r^2 = 0.90$) and a fit uncertainty that is clearly smaller than the class widths. Accuracy of runoff values, record length and availability of pre-1850 values[11–13] make Dresden the most suitable station to study middle Elbe floods.

The Oder record was extended using monthly maximum stage from Krosno from 1905 to 1936 (ref. 19), and daily runoff from Eisenhüttenstadt (40 km downstream of Krosno) from 1920 to 2002 (GRDC, http://www.wetteronline.de). Although the correlation in Fig. 1b is high ($r^2 = 0.91$), our constructed Oder record may miss some minor floods between 1850 and 1904 because for that interval only flood measurements[8,14], not continuous data, are available. The correlation between Eisenhüttenstadt and Polecko (monthly runoff from 1946 to 1987) is good ($r^2 = 0.84$). Precise information on

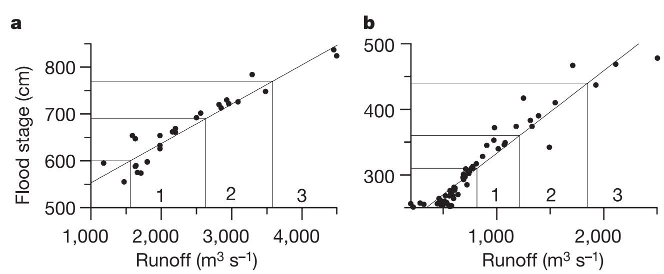

Figure 1 Classification of flood magnitudes (1: minor, 2: strong, 3: exceptionally strong) using linear regressions between flood stage and inferred runoff. Thresholds were applied to documented floods (before 1850) and measurements (after 1850). **a**, Elbe, station Dresden, 1852–92, $n = 27$, $r^2 = 0.90$, $\sigma_s = 24$ cm, $\sigma_r = 286$ m^3 s^{-1}, thresholds: 600/690/770 cm and 1,560/2,630/3,580 m^3 s^{-1}. **b**, Oder, stations Krosno (stage) and Eisenhüttenstadt (runoff), 1891–1936, $n = 58$, $r^2 = 0.91$, $\sigma_s = 18$ cm, $\sigma_r = 143$ m^3 s^{-1}, thresholds: 310/360/440 cm and 815/1,215/1,850 m^3 s^{-1}. n, data size; r, correlation coefficient; σ_s (fit uncertainty in stage) $= (\chi^2/(n-2))^{1/2}$; χ^2, sum of squares; σ_r (fit uncertainty in runoff) $= \sigma_s$/slope. In **a** and **b**, the widths of magnitude classes are about 3–4 times larger than the fit uncertainties.

stage–runoff relation seems not to be available[9] owing to war chaos and divided responsibilities. For the interval 1891–1936 the high correlation/low fit uncertainty (Fig. 1b), however, indicates stability of the stage–runoff relation at upper values. In terms of record length, stability of stage–runoff relation and availability of pre-1920 values[8,14,19], Krosno/Eisenhüttenstadt is suited to analyse floods of the middle Oder, although not of the same quality as Dresden for the Elbe.

Elbe and Oder floods (magnitudes 1–3) show a clear seasonal dependence, with winter floods occurring mainly in February–March (Elbe, Oder) and summer floods in June–July (Elbe) or August (Oder). (For the Elbe from 1021 to 2002, the number of floods in January/February/…/December is 51/76/81/35/18/38/35/25/8/4/6/27; for the Oder from 1269 to 2002, the number of floods is 19/24/50/30/25/23/27/34/15/9/3/11.) Before 1850, of 103 Elbe winter floods that allowed unambiguous distinction, 91 were connected with a frozen river (documented in the Weikinn/CLIMDAT sources); for the Oder, the number is 28 out of 34 events. Data (Supplementary Information) show further that during 1930–70, only 2 out of 13 Elbe winter floods were influenced by freezing; for the Oder, the number is 3 out of 20; in both rivers, the last ice flood occurred in 1947. For summer floods at Dresden and Eisenhüttenstadt, the 100-yr runoff value, estimated by fitting a generalized extreme value (GEV) distribution to bi-monthly maxima[20], is 3,900 $m^3 s^{-1}$ and 2,500 $m^3 s^{-1}$, respectively. The correlation coefficients (calculated separately for winter and summer) between Elbe and Oder flood time series (constructed using monthly magnitude data with magnitudes for months without a flood set equal to zero) during 1500–2002 are around 0.3. Analyses of extracted intervals confirmed that these values have not changed over time. The weak relation between individual Elbe and Oder floods shows that orographic differences between both catchment areas are effective. This is illustrated by the following examples of major floods (see Supplementary Information): August 1501 (Elbe, Oder), February–March 1784 (Elbe), April 1785 (Elbe, Oder), July 1997 (Oder), August 2002 (Elbe).

During the interval ~1820–2002, the estimated occurrence rate[21,22] (see Methods) of winter floods of the Elbe steadily decreased, while that of summer floods did not change significantly (Fig. 2). The statistical test (see Methods), using measured runoff (Q) data from Dresden (1852–2002), confirmed these results at the 90% level—not only for the magnitude classes that we used ($Q \geq 1{,}560/2{,}630\ m^3 s^{-1}$), but also for other thresholds (1,450/1,800/2,200/3,000 $m^3 s^{-1}$), attesting to the robustness of the trends. Using data from stations Děčín and Barby gave similar test results. In the Oder during ~1800–1920, occurrences of winter as well as summer floods increased (Fig. 2). This should, however, be interpreted cautiously, as data quality in 1850–1904 is reduced. For 1920–2002, the Oder exhibited the same trends as the Elbe: less winter floods and no change in summer flood occurrence, confirmed by the test for various thresholds ($Q \geq 600/700/815/1{,}110/1{,}215/1{,}350/1{,}500\ m^3 s^{-1}$). (Using monthly runoff data from Oder station Polecko did not reveal significant trends owing to the shortness of the record.) Attempts to identify short-term changes (last ~30 yr) or changes in class-3 flood occurrence lacked statistical power.

To evaluate whether uncertainties in the stage–runoff relation (Fig. 1) are small enough not to corrupt trend test results, a simulation study was carried out (see Methods). This showed that adding noise up to twice the uncertainty ($2\sigma_r$) to the runoff time series left results unchanged, making the trends robust also in that respect.

To test whether the observed trends over the past ~80–150 yr were the effect of increases[9,23] (since ~1900) in total reservoir size, we constructed flood records (Supplementary Information) that correct for this effect (see Methods) and repeated the trend test. In case of heavy floods (classes 2–3), the results were the same as for the uncorrected records (Fig. 2 and Supplementary Table). This means that for the rivers Elbe and Oder, reservoir sizes are too small to influence the occurrence of heavy floods. On the other hand, the occurrence of minor floods (class 1) can be affected (Supplementary Table). Caution is required as regards the upward trend of reservoir-size-corrected summer floods (classes 1–3) of the Elbe. Because in practice total reservoir size cannot be used to 100%, the test

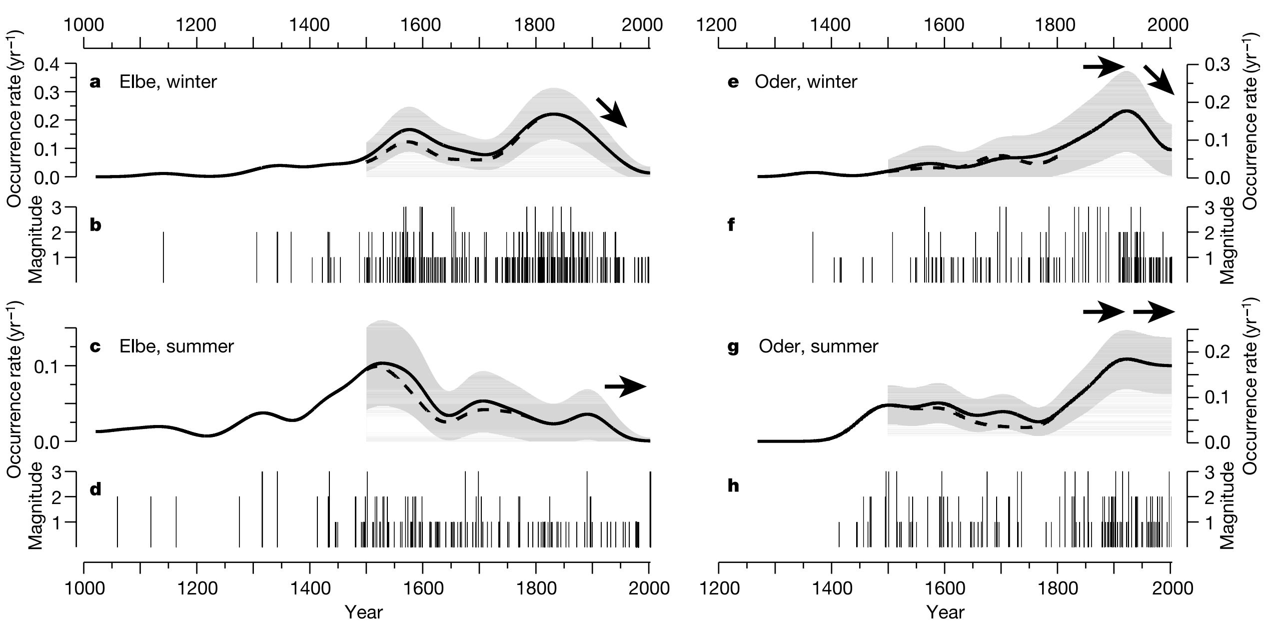

Figure 2 Occurrence rates of heavy floods (magnitude classes 2–3) in central Europe. **a**, **b**, Elbe, winter; **c**, **d**, Elbe, summer; **e**, **f**, Oder, winter; **g**, **h**, Oder, summer. Flood data from Weikinn's sources[10] (Supplementary Information) (**b**, **d**, **f**, **h**) were analysed using a gaussian kernel, a bandwidth of 35 yr and bootstrap simulations (see Methods). This yielded (**a**, **c**, **e**, **g**) occurrence rates (solid lines) and 90% confidence bands (grey); occurrence rates using data from CLIMDAT[16] (Supplementary Information) for 1500–1799 are shown as dashed lines. Records before 1500 are probably not homogenous (no confidence bands drawn). Arrows indicate the results (downward/no trend) from the statistical test (90% level) for trend in the flood occurrence rate (Elbe, 1852–2002; Oder, 1850–1920 and 1920–2002); results for uncorrected and reservoir-size-corrected data are identical. For occurrence rates and trends including data on minor floods (class 1), see Supplementary Information.

becomes liberal for upward trends (see Methods), and the apparent upward trend may be an artefact. Because land-use changes[9,18] over the past ~80–150 yr (for example, deforestation in the mountainous catchment parts) would, if effective, reduce retention capability[24] and induce upward trends (which are absent for heavy floods), we assess their influence as negligible.

To assess whether climate variations had an influence on detected downward trends of winter flood occurrence and on absent trends of summer flood occurrence, we analysed records of precipitation in central Europe. Data[25] consist of homogenized monthly estimates from 1900 to 1999 for gridboxes at 2.5° latitude by 3.75° longitude resolution. The gridbox centred at 50° N, 15° E contains nearly the entire catchment area of the Elbe at Dresden and parts of the catchment area of the Oder at Eisenhüttenstadt; the gridbox at 50° N, 18.75° E contains eastern and southern parts of the Oder catchment, but mainly other areas. Winter (November–April) and summer precipitation was treated separately. Statistically significant trends in the occurrence of 25-yr maxima were detected (Fig. 3). Comparing these trends with those of extreme floods (Fig. 2) over the past ~100 yr roughly indicates a causal influence of extreme precipitation events on floods. However, besides parallel trends (winter floods/precipitation at 50° N, 15° E; summer floods/precipitation at 50° N, 18.75° E) we find also non-parallel (but not opposing) trends (Figs 2, 3). We explain this discrepancy as follows. (1) Limited temporal resolution (floods, precipitation) and (2) limited spatial resolution (precipitation) may blur a causal connection. (3) Runoff-influencing factors are having an effect. Such factors presumably consist less of reservoir-size or land-use changes (see above) and more of climate changes. In the case of winter floods, a factor could be the reduced rate of strong river freezing (that is, potentially flood enhancing) events (see above and ref. 1). Reduced freezing may have been caused by warming[26] or increased pollution of river waters. Elevated winter temperatures could also have had an effect via a reduction of occurrence of frozen soil, which has low absorbing capacity[24].

Figure 2 indicates further that the flood occurrence rates increased markedly during the fourteenth and fifteenth centuries. These increases are probably an artefact caused by inhomogeneous records: fewer documents about floods from that period—compared with following periods—were written (before the invention of printing) or have lasted to the present day, or flood perception was different[1], leading to missed events. A maximum in flooding rate was reached in the sixteenth century (presumably in its latter half), and was more pronounced in case of the Elbe (Fig. 2). Rivers in central and southwest Europe during the sixteenth century had a similar increase[15], which was attributed to higher precipitation. The subsequent reduction in Elbe winter flood occurrence to a low around 1700 (Fig. 2a) might reflect the cold and dry climate of the Late Maunder Minimum[27]. However, the Oder (Fig. 2e) shows no such reduction. Major reductions in length[28] of the middle Elbe were made during 1740–1870, and reductions in length of the middle Oder were made during 1745–1850. A consistent (winter/summer, Elbe/Oder) signal of these length reductions is not seen in the flood data (Fig. 2). This suggests a minor influence of length reductions on the occurrence of heavy floods—a detailed hydrological model would be required to quantify that influence.

Although extreme floods with return periods of 100 yr and more occurred in central Europe in July 1997 (Oder) and August 2002 (Elbe), there is no evidence from the observations for recent upward trends in their occurrence rate. Global climate changes affect many and various processes in regional hydrology, such as river and soil freezing in the case of winter floods under continental climate. Long, continuous, seasonally and regionally resolved flood records like those for the Elbe and Oder should facilitate evaluation of future trends using coupled atmospheric–hydrological models[24]. □

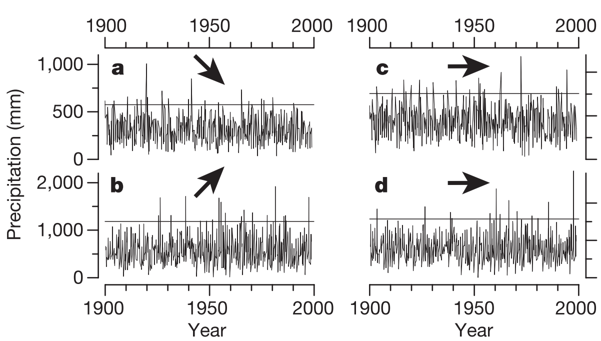

Figure 3 Occurrence of extreme precipitation events in central Europe during the twentieth century. Data are gridded monthly precipitation values[25] at 50° N, 15° E (**a**, **b**) and 50° N, 18.75° E (**c**, **d**) during winter (November–April) (**a**, **c**) and summer (May–October) (**b**, **d**). Shown as horizontal lines are 25-yr maxima (**a**, 576 mm; **b**, 1,182 mm; **c**, 755 mm; **d**, 1,573 mm), obtained by fitting a GEV distribution[20]. Arrows indicate the results (upward/downward/no trend) from the statistical test (90% level) for a trend in the occurrence of 25-yr maxima.

Methods

Occurrence rate estimation

Kernel estimation[21,22] allows detailed inspection of time-dependent flood occurrence rates and assessment of significant changes with the help of confidence bands. We used a gaussian kernel, K, to weigh observed flood dates, $T(i)$, $i = 1,\ldots, N$ (number of floods), and calculate the occurrence rate, λ, at time t as:

$$\lambda(t) = \Sigma_i K((t - T(i))/h) \quad (1)$$

Selection of bandwidth ($h = 35$ yr) was guided by cross-validation[21]. Confidence bands (90%) around $\lambda(t)$ were determined using a bootstrap technique: N simulated floods were drawn from $T(i)$ with replacement and simulated λ calculated. This procedure was repeated 2,000 times, and a percentile-t confidence band[21] calculated. Detected trends in occurrence rate were confirmed for the measured interval (1850–2002) using the statistical test in ref. 29. Under the null hypothesis H0 'constant occurrence rate', the quantity $[\Sigma_i \mathrm{T}(i)/N - (t_u + t_l)/2]/[(t_u - t_l)/(12N)^{1/2}]$ is standard-normally distributed. Here t_u is the upper bound of the observation interval (September 2002), t_l the lower bound (1850). H0 was tested against one-sided alternatives (for example, 'λ increases') at the 90% level. Robustness of test results against uncertainties in stage–runoff relations was confirmed as follows. For each station, 2,000 simulated runoff time series were generated by adding noise ($2\sigma_r$, which means a conservative approach) to measured data; simulated flood dates were determined and trend tests repeated. This yielded the same average trends.

Reservoir-size correction

The time-dependent total volume, $V(t)$, of reservoirs above a station that can be employed for flood management was used to construct corrected flood records that assume a constant reservoir size at present level, V_p. $V(t)$ increased monotonically since ~1900; data[9,23] are given in Supplementary Information. To calculate reduced runoff, Q_r, for a flood that could have been obtained if $V(t)$ equalled V_p, we 'cut off' the flood peaks in daily runoff, $Q(t)$:

$$\int (Q(t) - Q_r)\mathrm{d}t = V_p - V(t) \quad (2)$$

where the integral is over the time a flood lasted. Q_r was then sorted into the same magnitude classes as in Fig. 1. This was carried out for all detected floods (Elbe, Dresden; Oder, Eisenhüttenstadt) in the instrumental period, yielding records (Supplementary Information) that are not influenced by changes in reservoir size. Note that in practice utilization of the total reservoir size is less than 100%, making the Q_r estimate a lower bound. This further implies that trend tests using reservoir-size-corrected records become conservative (liberal) as regards downward (upward) trends.

Received 16 May; accepted 16 July 2003; doi:10.1038/nature01928.

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Supplementary Information accompanies the paper on **www.nature.com/nature**.

Acknowledgements We thank J. Jacobeit, J. Luterbacher and M. Schulz for comments, and N. Conrads, H. Engel, W. Fröhlich, T. Lüllwitz, J. Munzar, R. Oppermann as well as GRDC (Germany) and NOAA (USA) for data. This work was supported by the Deutsche Forschungsgemeinschaft.

Competing interests statement The authors declare that they have no competing financial interests.

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Radiometric dating of the Siloam Tunnel, Jerusalem

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The historical credibility of texts from the Bible is often debated when compared with Iron Age archaeological finds (refs. 1, 2 and references therein). Modern scientific methods may, in principle, be used to independently date structures that seem to be mentioned in the biblical text, to evaluate its historical authenticity. In reality, however, this approach is extremely difficult because of poor archaeological preservation, uncertainty in identification, scarcity of datable materials, and restricted scientific access into well-identified worship sites. Because of these problems, no well-identified Biblical structure has been radiometrically dated until now. Here we report radiocarbon and U–Th dating of the Siloam Tunnel[3–10], proving its Iron Age II date; we conclude that the Biblical text presents an accurate historic record of the Siloam Tunnel's construction. Being one of the longest ancient water tunnels lacking intermediate shafts[11,12], dating the Siloam Tunnel is a key to determining where and when this technological breakthrough took place. Siloam Tunnel dating also refutes a claim[13] that the tunnel was constructed in the second century BC.

The Siloam Tunnel carries water into ancient Jerusalem from the only perennial spring of the region, the Gihon (Fig. 1). This tunnel has attracted the attention of many scholars, who have yet to solve some of its mysteries[3–13]. Most scholars ascribe the Siloam Tunnel to King Hezekiah (727–698 BC), following the biblical verses (2 Kings 20:20, 2 Chronicles 32:3,4) narrating that this Judahite king constructed a waterwork that "brought water into the city". In addition to the biblical record, the Siloam Tunnel's association with Hezekiah also relies on the palaeography and philology of the monumental Siloam inscription found close to the Siloam Tunnel's outlet (refs 14, 15 and references therein). However, the name of King Hezekiah is not mentioned in the inscription, unlike other monumental inscriptions of the Levant, which often praised monarchs for their architectural achievements. If the assumed date of the inscription is correct, it can still be argued that the inscription could be a later copy of a literary narrative, such as the 'Chronicles of the Kings of Judah', so the Siloam Tunnel itself may be older than the inscription. Such a view could be supported by the unique style, differing from most other North-Semitic inscriptions[15]. According to ref. 13, a

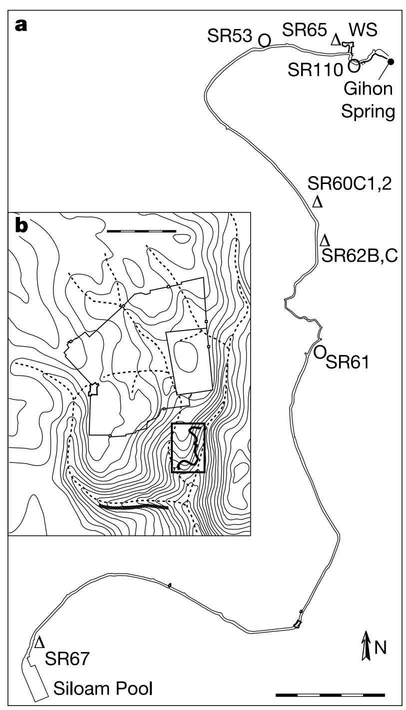

Figure 1 Location map. **a**, Plan of the Siloam Tunnel (Long. 35.17°; Lat. 31.68°) with the location of dated samples. Scale bar, 50 m. Circle, plant fragments within plaster, dated by ^{14}C AMS; triangle, speleothem sample dated by ^{230}Th–^{234}U thermal ionization mass spectrometry. WS, Warren Shaft. **b**, Relation of the Siloam Tunnel (bold line) to the topography of Jerusalem and the present city walls. The Siloam Tunnel conveyed the water of the Gihon Spring into the Siloam Pool within the original core of Jerusalem. Contours are 10 m (vertically) apart. Scale bar, 500 m.