

Lessons from a 500-year Record of Flood Elevations

By James H. Eychaner

Abstract

Peak elevations of 14 floods as early as 1501 on the Danube River at Passau, Germany, reveal great variability in the actual intervals between floods for average historical recurrence intervals commonly used in planning for community flood safety. Only half of the intervals between 50- and 100-year floods were within 50 percent of the nominal average interval. Flood events greater than the 50-year flood occurred at intervals of 4 to 192 years since 1501, and the 50-year flood of 2002 was followed only 11 years later by a 500-year flood. Similarly, the intervals between 5-year floods since 1955 ranged from 5 months to 16 years, and only half were within 2.5 to 7.5 years.

Floods vary along any river. The three largest floods at Passau in the past century had a 10-fold range of recurrence intervals and peak elevations that differed by more than 200 cm. The same floods became nearly identical 190 km downstream at Melk, Austria, where the recurrence intervals were all about 170 years and the peak elevations were all within 5 cm.

In the United States, fewer than 500 locations have observed flood records as long as 90 years, so 100-year flood estimates have large individual uncertainties for most stream reaches. Climate variability and change will add unquantified uncertainties to future flood risk estimates. In 1816 the designers of the original Erie Canal project had little knowledge of flood risks, which led to unexpectedly high maintenance costs and reduced in-service periods during the canal's 80-year service life. Two hundred years later, much better information about floods and construction engineering is available, yet without confidence that future flood climate will be like the past, project designers face larger, unquantified uncertainties than were assumed a few decades ago. As a result, engineering projects intended to protect from or withstand flooding could become more expensive in the future, because they might need larger safety margins in design and perhaps unexpected repairs after failures.

People enjoy the benefits of living close to water, and flood hazards often accompany those benefits. When people recognize the full price of living near a flood hazard, they are more likely to make their choice consciously and responsibly.

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Key words: flood frequency analysis, uncertainty, recurrence interval, climate change, 100-year flood, flood safety, planning, Danube River, Passau.

Editorial Conventions

While this report is intended for an English-speaking general audience in the United States, it draws heavily on data sources from German-speaking central Europe. To minimize errors in working with both languages, the following conventions are used in this report. The primary goal is that the text flow smoothly and understandably in each section.

Names and technical terms: Where English and German use different names for the same geographical feature, both are provided at first use but only one later in the text. In particular, the Danube River (die Donau) is consistently Danube and the Altes Rathaus (Old City Hall) is consistently Rathaus. Similarly, original German terms, government agency names, and report titles are used in most instances, with English translations in parentheses as needed. In a few contexts a different pattern is used for clarity.

Dates: U.S. sources normally abbreviate dates as month-day-year, while German sources use day-month-year. Thus in the United States 08/06/2013 or 08.06.2013 would represent August 6, 2013, but it would be understood as 8 June 2013 in Germany.

This report uses the German order in all cases except for three photographs that carry a U.S.-ordered date supplied by the camera. In text, the month name is spelled out. Numerical abbreviations, in German order, appear in figure 4 and tables 3 and 6.

Reference elevations: The local zero value of a stream gage (Pegel) elevation scale is the gage datum or gage zero (Pegelnullpunkt). Elevations near Passau are referred to sea level (Normalnull) for regional comparisons; the U.S. reference elevation NGVD (National Geodetic Vertical Datum) is not defined there.

International system (SI) units: German sources present the hydrologic data in SI units of meters (m), centimeters (cm), and cubic meters per second (m^3/s). Because this report emphasizes the relative, rather than absolute, magnitude of different flood events, values generally are retained in SI units and not converted to U.S. conventional units of feet (ft), and cubic feet per second (ft^3/s). Again, in a few contexts a different pattern is used for clarity.

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Lessons from a 500-year Record of Flood Elevations

By James H. Eychaner

Introduction

Humans have always recorded extraordinary floods, both in oral traditions and in physical markings appropriate to the setting and available materials. Damages caused by floods are so great that humans try to protect their communities from similar losses in the future. The simplest idea is that if one flood could rise to a marked level, another one could do so in the future.

Among the many existing records, this report will emphasize the numerous flood elevation marks since 1501 at Passau, Germany, on the Danube (Donau) River, supplemented by a smaller number of flood marks downstream at Melk, Austria (figure 1). These long records show that the intervals between large floods are surprisingly uncertain, despite the apparent certainty of the label "100-year flood."

People commonly choose to live or work in places at risk of flooding, and they do so because the benefits are greater than the costs of periodic repair. Where the choice is individual and conscious, it can be quite reasonable, but when it is not voluntary or purposeful, flood losses can be perceived as unfair.

The purpose of this report is to document the long Danube River records for an American audience and to help individuals in the United States make well-informed decisions to balance the risk and reward of living and working near hydrologic hazards, by examining uncertainties on the risk side.

Floods occur in patterns that generally are known, but with huge uncertainty in detail. The records of floods in the upper Danube basin over the past 500 years reveal how great the uncertainties are. Governments, like individuals, always work in the tension between spending present resources to prevent future harm and spending to repair damage that already has occurred. The decisions of individual citizens to accept risks of flooding, including the uncertainty of the risk magnitude, are inseparable from their individual responsibilities to pay for repairs when damage occurs.

Acknowledgements

This report would not have been possible without the kind cooperation of many individuals. The author particularly thanks Ms. Claudia Veit, archivist, City of Passau; Mr. Helmut Wagner, supervising engineer at the Bavarian Water Management Office in Passau; Dr. Alfons Vogelbacher, flood forecast engineer with the Bavarian Environment Agency in Munich; and Ruth and Russell Burgess of Sacramento, California, for the photographs in figure 5. This report was substantially improved through careful technical reviews by Dr. Robert Holmes, national flood hazard coordinator for the U.S. Geological Survey, and Dr. Julie Kiang.

Fig. 1 Location map



The Price of Living with Flood Hazards

"You pay a price to live here, but it's worth it." That idea repeats throughout the human experience. The owner of a beach-side restaurant in North Carolina's Outer Banks, rebuilding after a hurricane, said it to a national television reporter. A long-time resident of Hawaii said it to a newcomer thinking about the high cost of living. A rancher in rural Montana might recognize it in limited access to advanced medical care. The price might be paid in many small increments, or it might seem to be zero until suddenly it's a huge surprise.

Floods surprise many people. They value the benefits of living or working near a river, lake, or ocean. Perhaps they're not even conscious of the benefits, but when a flood arrives, the price must be paid. Knowing the price in advance can help each person decide if the benefits are worth the price.

Floods don't happen often, but when they do, the costs are huge. Flood waters are always filthy. They carry sand and mud, mold spores and bacteria, shredded vegetation and dead animals. Removing the stink of rotting organic matter and restoring basic sanitation to a flooded home takes tremendous effort. Lost family photographs and documents, toys, mementos, and computer records are irreplaceable. The comforts of continuity disappear.

Repair of a flooded home begins with throwing away everything that got wet: tools and toys, documents and mementos, carpets and upholstered furniture, warped wood flooring and cabinets, even the electrical outlets and plaster on the walls. Flooded automobiles and electrical appliances are usually unsafe to reuse. Recovered mementos become especially valuable because they are so few.

Physical labor for the initial cleanup commonly comes from the home's residents, if they are able, or from their extended family, friends, neighbors, and unknown volunteers. The effort can be overwhelming. After extensive flooding, entire communities can be overwhelmed. Just removing the waste piles in front of each flooded home becomes a huge task. The financial cost to repair a flooded home can exceed its previous value. A flooded community must replace individual and community investments that accumulated over many decades.

Who pays those costs, and how should a community decide who pays which share? One option would assign the entire cost to those whose property is damaged, effectively requiring them to be self-insured. Immediately after a flood, of course, they are least ready to bear a large financial burden in addition to the unavoidable physical and emotional burdens. Another

option grows from the near universal response of human communities to assist their neighbors after a catastrophe. That neighborliness is expressed in disaster relief after particularly large floods, primarily programs organized through governments and funded by all taxpayers. But neither governments nor charitable organizations ever pay for all the costs of flood damage to private property. The middle option is to require individuals who live in identified hazard zones to carry insurance against flood damage up to a defined limit and to regulate construction in those zones, in exchange for a commitment from the broad community to share the cost of damage above the limit through disaster assistance programs.

In the United States, flood insurance was established by Congress through the National Flood Insurance Act in 1968 (P.L. 90-448). A series of amendments beginning in 1973 made the insurance mandatory for properties in identified hazard zones that are security for Federally-insured mortgage loans and regulated new construction there. In 2012 Congress required that premium rates increase over a few years to balance total premiums with total losses. Current law is codified at 42 U.S.C. Chapter 50 §§ 4001-4130. When extreme flooding causes damage beyond the identified hazard zones, low interest loans from the Federal government also provide resources for damage repair and disaster recovery. Complete information on the National Flood Insurance Program is at <http://www.floodsmart.gov/>.

Flood Recurrence Intervals—Statistics, Regulation, and Uncertainty

In the United States, individual responsibility to insure against flood damage is limited to a hypothetical flood that has a 1-percent annual exceedance probability. That limiting flood is defined by a 1 in 100 chance of being equaled or exceeded in any one year; it has a long-term average recurrence interval of 100 years and is often referred to as the "100-year flood" (Holmes and Dinicola, 2010). Although at first glance the definition appears to be a clear and complete statistical statement, in practice observational data are inadequate for most locations and several important assumptions are unproven. This report will use the wording "100-year flood," as that is most common among the general public.

Floods of other average recurrence intervals are similarly defined. A 50-year flood has 1 chance in 50 (2 percent) of being equaled or exceeded in any one year, a 200-year flood has 1 chance in 200 (0.5 percent) of being equaled or exceeded in any one year, and so on.

The percent chance of an X-year flood occurring in a single year is simply 100 divided by X. In discussing specific flood events, this report will use "X-year flood" to mean one with a historical average recurrence interval greater than or equal to X years. Thus a 200-year flood event is also a 100-year and a 50-year event.

Abundant scientific literature is available discussing the computation of flood recurrence intervals in general and at specific locations. Most analyses of flood hydrology are based on discharge, the volume of water passing a location in a unit of time; this report uses flood elevations, because a much longer record is available. Direct statistical analysis (IACWD, 1982) to estimate the 100-year flood is possible only at the relatively few locations where an annual series of maximum instantaneous flood discharges has been recorded. In the United States, the taxpayers have supported such records for at least 60 years at fewer than 2,600 locations, for at least 90 years at fewer than 500, and for at least 120 years at only 11 (<http://waterdata.usgs.gov/nwis>). For comparison, the total area of the nation is about 3,800,000 mi², so there are perhaps 3,000 stream reaches that drain watersheds of 1,000 mi² and 300,000 reaches that drain 10 mi². In urban areas, 100-year flood estimates are needed for watersheds as small as 1 mi². For reaches without sufficient data for direct analysis, 100-year flood estimates are derived from indirect statistical analysis of flood records at other locations in a hydrologically similar region.

Most areas where serious floods can occur in the United States have been mapped consistently, in a regulatory framework that identifies zones at risk of inundation, to provide a risk basis for flood insurance rates (<http://www.floodsmart.gov/>). The "regulatory flood" or "base flood" associated with these hazard zones is routinely established through a science-based rule making process targeted to a 100-year flood at the historical average recurrence interval. In addition to historical flood data, the process accounts for previously established regulatory values, the effects of flood-control reservoirs, and changes in land use in the watershed.

A flood peak observed at different locations on the same stream during the same event commonly represents a different recurrence interval at each location. If an extreme storm drops enough rain on one branch of a river to cause a 100-year flood, but no rain falls over another branch, the flood wave downstream from the junction of the two branches might have a recurrence interval of only 10 years. Conversely, a storm that produces a 25-year flood simultaneously in each branch might form a 100-year flood downstream.

Because of this wide spatial variability of recurrence intervals and incomplete discharge data during an interval of flooding, news accounts usually convey an inaccurate understanding to the public. The media necessarily simplify the story by reporting the greatest damage and largest recurrence interval estimated at any location. The public makes the easy error of assuming those reports characterize the entire flood area, leading to a perception that 100-year floods occur "too often."

Predicting future flood risk from statistical analysis of past floods also assumes the future will be like the past. Abundant evidence shows that climate variability and change will bring a future unlike the past (Milly and others, 2008; IPCC, 2012). Analysis of historical data, therefore, can only provide estimates of historical recurrence intervals. The extent to which flood risk will change in the future is as yet unknown. It is an unquantified uncertainty.

Even if the future is like the past, flood estimates for various recurrence intervals are much more accurate when they are interpolated from data rather than extrapolated. For example, if 60 years of flood data are available for a certain location, the 20-year flood will be estimated much more accurately than the 200-year flood. Estimates for an average recurrence interval one third of the observed record length are generally accurate, but uncertainty increases consistently as the target recurrence interval increases and becomes quite large for the largest historical flood at a location or any potentially larger flood.

A flood will not occur at precisely the discharge of a regulatory 100-year flood, nor will one occur at intervals of precisely 100 years. Floods form a continuous distribution. The definition of recurrence interval includes the idea of counting floods larger than the reference level, not merely equal to it. Thus a home or business located just above the estimated 100-year flood level is not protected from all flooding. Larger floods are certain to happen, just not as often, on average.

The 500 years of flood elevation data at Passau offer a way to explore these concepts. Although the precision and completeness of the data are imperfect, the length of the records allows several useful interpretations not possible from more common, shorter records.

Records of Floods in Central Europe

Extreme floods that occurred during 23 separate years between 1012 and 1784 on major rivers in Bavaria, the largest federal state in Germany, were described by Wüllner and Vogelbacher (2004), who drew on an extensive catalogue of European source documents (Weikinn, 1958-2002). July 1342 had particularly extreme and widespread flooding. At Passau, 33 flood years between 1173 and 1970 were identified by Mühldorfer (1990) from local documents (table 1).

In addition to the dates of floods, high-water elevation marks have been maintained on stable structures in many communities (Wüllner and Vogelbacher, 2004). On the Danube, flood marks as early as August 1501 can be found at Passau, Germany, and Melk, Austria, among many other locations (figure 2).

Out of these occasional records grew an awareness of the value of a more complete system to record floods and other hydrographic data. In Bavaria, a network of daily water-level measurements at 65 sites on navigable rivers began in 1821 (Wüllner and Vogelbacher, 2004, p. 56). In 2014, about 700 stream gaging stations were operated by several State Offices for Water Management (Landesamt für Wasserwirtschaft) under the Bavarian Environment Agency (Bayerisches Landesamt für Umwelt, <http://www.lfu.bayern.de/>). Recognizing that complete protection from floods is impossible, Bavaria operates a flood warning system to reduce flood danger and damage, as the other federal states in Germany also do (Bavarian Environment Agency, 2013). Elevation and discharge data for all stream gages in Bavaria is available from the Flood Warning Service (Hochwassernachrichtendienst) at <http://www.hnd.bayern.de/>.

Downstream from Passau, the Hydrographic Service of Upper Austria (Hydrographischer Dienst Land Oberösterreich) operates a gage network; their data are at http://www.land-oberoesterreich.gv.at/cps/rde/xchg/ooe/hs.xsl/hydrographischer_dienst_DEU_HTML.htm. Further downstream near Melk, the Hydrographic Service of Lower Austria (Hydrographischer Dienst Niederösterreich) operates a gage network; their data are at <http://www.noel.gv.at/ExterneSeiten/Wasserstand/hm/wndcms.htm>.

Flood Records at Passau

Passau sits at the confluence of the Danube, Inn, and Ilz Rivers (figure 1), above a narrow flood plain confined by erosion resistant hills (<http://www.passau.de>, <http://en.wikipedia.org/wiki/Passau>, <http://de.wikipedia.org/wiki/Passau>). The Danube, which flows from Germany's Black Forest across central Europe to the Black Sea, has been a major route for travel and trade since prehistory, and Passau has been inhabited for more than 2,000 years. The drainage area of the Danube watershed at the three-river confluence is 76,643 km² (29,592 mi²) or about 9 percent of that at the river's delta 2,225 km downstream. The largest flood peaks at Passau occur when rapid snowmelt in the Inn watershed (26,072 km² and mostly in the Alps mountains) arrives during extreme rainfall in the lower-elevation Danube watershed, as in 1954 and 2013 (Wagner and Duschul, 2004; Belz and others, 2013).

What Flood Elevation Data are Available?

Water levels have been recorded systematically since at least 1957 at four gaging stations within 4 km of the three-river confluence and since 1901 at two stations on the Danube within 32 km (table 2). The highest peak discharges since 1827 have been calculated for one station on the Danube and one on the Inn. In addition to these scientific data, peak flood elevation marks are displayed on the tower of the old city hall (Altes Rathaus) for floods as early as 1501 (figure 2). The tower location (48°34'30" N x 13°28'07" E) is about 750 m downstream from the Danube River at Passau gage and 700 m upstream from the confluence and the Passau-Ilzstadt gage. For this report, a single set of elevations was derived from multiple sources, which for some flood events were inconsistent.

The primary information source for early flood elevations is a diagram from the city archives shown in figure 3 and summarized in English in the left section of table 3. The diagram has the handwritten title Hochwasserskala am Rathausturm (Flood scale at the City Hall tower). It has a rubber stamp image Stadtbauamt Passau/Amt für Vermessung (Passau Building Authority/Surveying Office) with a date of 13 November 1991 above and a signature below.

Table 1: Flood years in Passau identified by Mühldorfer (1990).

1173	1439	1448	1456	1481	1501	1558	1595	1662	1682	1752
1785	1786	1787	1845	1862	1876	1883	1890	1895	1897	1899
1903	1905	1906	1920	1927	1929	1954	1956	1965	1966	1970

Figure 2. Photographs of the Passau high water scale in 2012.

a. Complete scale



b. Detail view

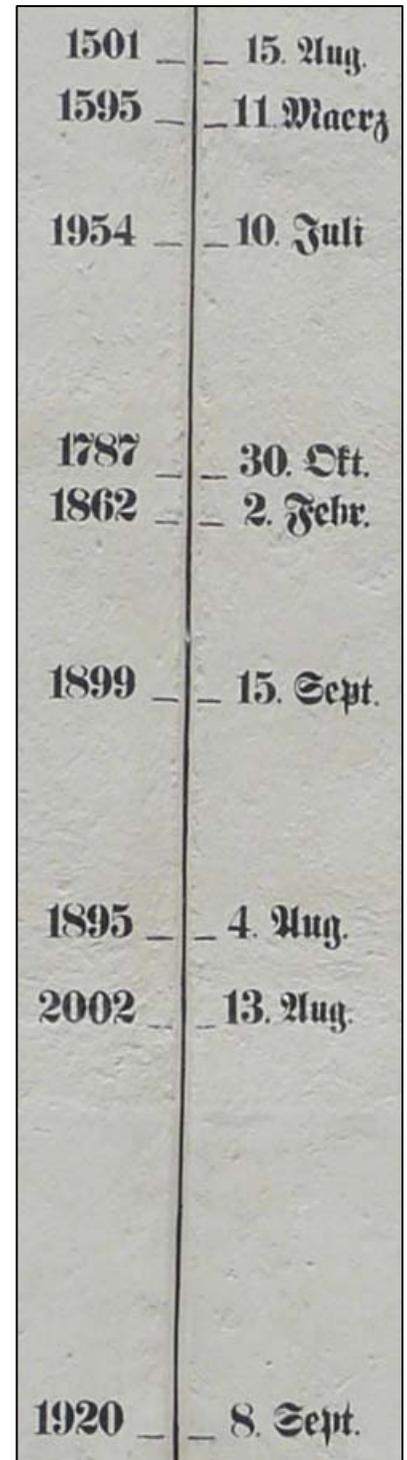


Table 2: Selected stream gages active in 2014.

Number	Name	Drainage area, km ²	Stream location, km above mouth	All flood elevations recorded since	Highest flood discharges calculated since
Data from http://www.hnd.bayern.de					
10088003	Danube River at Hofkirchen, Germany	47,610	2,256.90	1901	1826
10091008	Danube River at Passau, Germany	49,716	2,226.70	1956	1940
18008008	Inn River at Passau (Ingling), Germany	26,063	3.10	1921	1827
10092000	Danube River at Passau (Ilzstadt), Germany	76,643	2,225.25	1957	1861
10094006	Danube River at Achleiten, Austria	76,660	2,223.10	1901	1861
Data from http://www.noel.gv.at/Externeseiten/wasserstand/static/stations/207357/station.html					
207357	Danube River at Kienstock, Austria	95,970	⁽¹⁾ 2,017	1991	1862

⁽¹⁾ Estimated

The photograph of the flood scale in the diagram includes a water level (Wasserstand) for the 1920 flood but not the 1954 flood, so it must have been taken between those dates. The flood scale in the photograph probably was restored within a year or two after the 1920 flood.

The diagram appears to have developed in two stages, with the first depicted on the right and the second on the left. All dates shown in the archive photograph match equally-spaced horizontal lines in the central sketch, which suggests the sketch was drawn to record vertical intervals scaled from the surveying rod visible in the photograph (the values written vertically in figure 3). The lowest interval begins at a brass elevation reference mark identified as 295.71 m above sea level (über Normalnull), and the intervals are converted to elevations in the right-hand column. Elevations also are shown for a match point at the top of the stone cove molding (Hohlkehle) above the main foundation stones and for the pavement at the base of the tower.

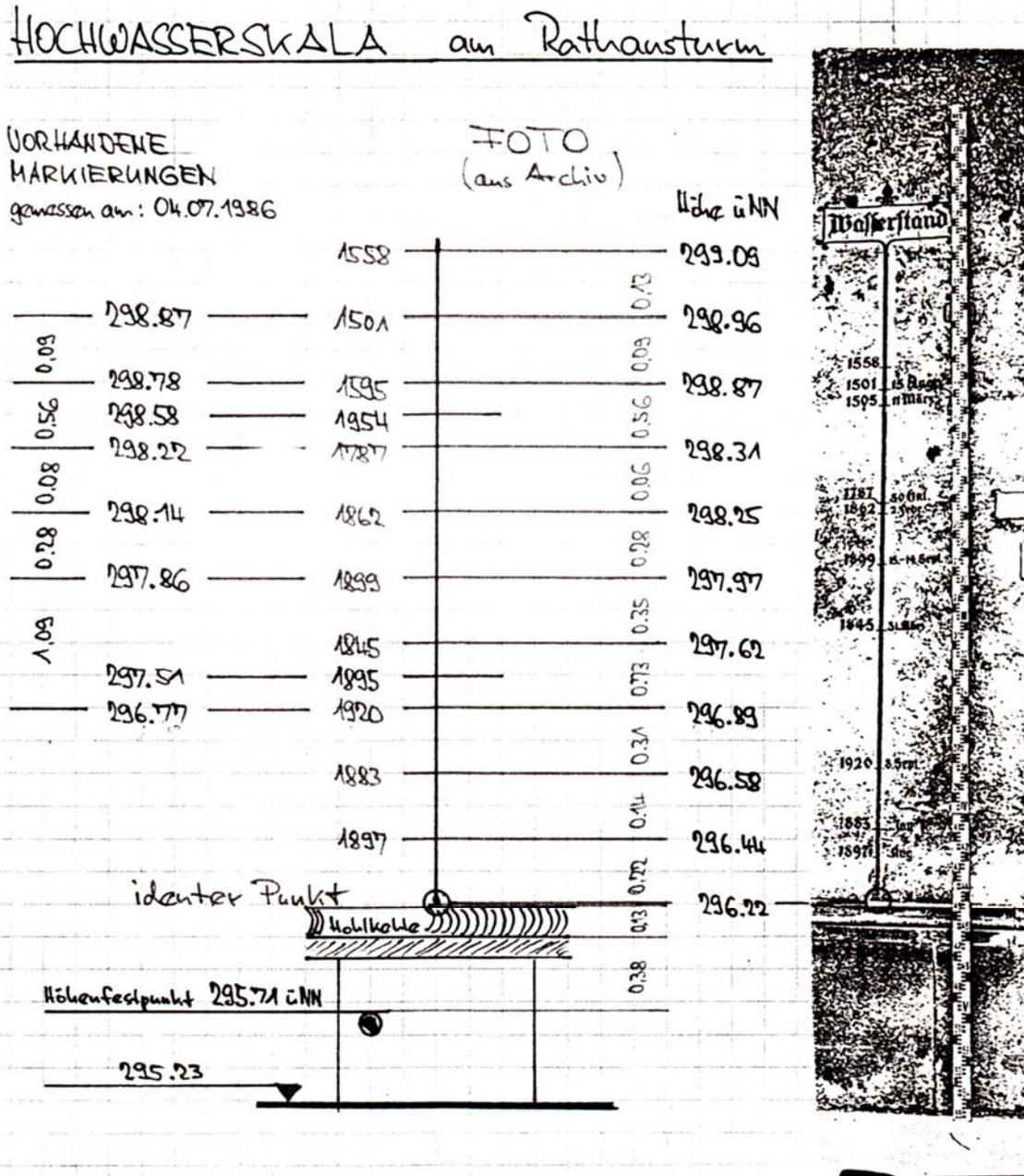
The second stage, at the left of the diagram, adds measurements taken on 4 July 1986 of the markings then present, showing elevations above mean sea level and intervals between pairs in common with the earlier photograph. Three of the five intervals agree to the 1-cm precision shown. The elevation interval between the floods of 1787 and 1862 is 6 cm in the photograph but 8 cm in the 1986 measurements. Similarly, 1899 and 1920 differ by 108 cm in the photograph but 109 cm in 1986. Two additional dates were measured in 1986, for 1895 and 1954, and four dates had disappeared (1558, 1845, 1883, and 1897). These elevations are 9 to 12 cm lower than the matching elevations shown to the right, probably because a different value was used for the elevation reference mark.

Information linking the flood marks on the Rathaus tower to the present gaging network comes from an unpublished table dated 27 February 2008 entitled Hochwasserstände in Passau (Flood levels in Passau) and provided by the supervisor of the water management office branch in Passau (Helmut Wagner, engineer, Wasserwirtschaftsamt Passau, written communication, 6 June 2012). The table shows the elevation of 22 overbank floods from 1954 to 2007, along with the 1501 flood, at four sites in the city. The table includes the gage height and sea-level elevation at the Danube River at Passau gage and an approximate elevation at the Rathaus tower.

Three floods are shared between the Wagner table and the marks on the Rathaus tower in 2012 (table 3, figure 2). Both sources record the 1954 flood at effectively the same elevation, and the 1954 flood was the largest in the period of systematic record keeping. Its elevation in the archive diagram is therefore a reasonable basis for a consistent set of elevations at the Rathaus. For this report, those elevations were taken as the values measured in 1986, if available, or as the values scaled from the archive photo offset by the difference from the 1986 measurement of the next higher or lower flood.

For 1501, however, the elevation displayed on the tower is about 60 cm lower than in Wagner's table. The higher value, used for this report, is based on interpolation from a longitudinal profile of several 1501 high water marks preserved in the old city both upstream and downstream from the Rathaus (Helmut Wagner, written communication, 28 December 2012).

Figure 3. Archive diagram of the Passau high water scale.



13.11.1991

Stadtbauamt Passau
Amt für Vermessung

Loide

The photo in the archive diagram shows a 1558 flood slightly higher than 1501, but no mark for 1558 was on the tower in 2012 or 1986 (figures 2 and 3). The only documentation of the 1558 flood was the mark on the tower and one source stating it was slightly smaller than 1501 (Helmut Wagner, written communication, 28 December 2012). For this report, the archive diagram value was used. This decision reverses the elevation order of the two earliest events, but the choice is not critical for the purpose of this report in examining uncertainties for 50- and 100-year floods.

For the flood of 2002, the elevation of the mark on the tower in 2012 (figure 2) can be interpolated between the known elevations for the floods of 1895 and 1920, resulting in a value of 297.38 m. This mark is inconsistent with data from the present gaging network, because its elevation is higher than the corresponding elevations at both the Danube River at Passau gage 750m upstream (297.27 m) and the Passau-Ilzstadt gage 700 m downstream (297.03 m). The average of the two gage values was used for this report, the same value as in Wagner's table.

An additional extreme flood reached its peak elevation at Passau on 3 June 2013 (http://en.wikipedia.org/wiki/2013_European_floods). Peak elevation at the Danube River at Passau gage was 1289 cm at 11:00 PM, or 69 cm higher than in 1954 (Belz and others, 2013, p. 32-33). The corresponding elevations are 299.35 m at the gage and 299.27 m at the Rathaus tower (table 3). A preliminary mark on the Rathaus tower on 24 July 2013 appears to show the 2013 flood was much greater than 1501 (figure 4). Extrapolating from the elevations measured in 1986 (table 3) shows that preliminary mark was about 299.38 m above sea level or about 3 cm higher than the flood peak at the upstream gage.

The elevation based on systematic measurements at the gage was used for this report. This accepted value is 11 cm lower than that shown in figure 4 and is lower than the accepted value for 1501 because of the 60-cm difference mentioned above. Either elevation for the 2013 peak is lower than the accepted 1501 peak, so the 2013 flood was the highest since 1501 but did not set a new record. Again, for the purposes of this report, the order of these two events is not critical.

How Accurate are the Elevations?

This report assumes that the flood elevations shown in table 3 are in correct order of relative elevation. The elevations generally are accurate within 10 cm, as discussed in this and the preceding sections. The two sources for the 1501 elevation, however, differ by 60 cm. The objectives of recording flood elevations

for display to residents and tourists can be different from the objectives of scientific data collection, so it is not surprising that the results differ. The elevations used in this report (table 3) are consistent with data from the present gaging network.

Scientific water-level data represent the surface elevation of still water by itself, without the variability of waves or any accumulation of debris piled up along the river bank. Stream gaging stations are designed to create a column of calm water connected to the live river, so that accurate and precise measurements are possible (Sauer and Turnipseed, 2010, p. 7-10). After a flood, lines of debris, mud, or wetting can be difficult to interpret without training (Benson and Dalrymple, 1967, p.11). Observations by untrained people might reflect the highest elevation of wetting, of structural damage from material that collapsed after erosion below, or of windrows of floating debris incrementally pushed up by waves. The maximum elevation water reached during a flood can be uncertain even immediately afterward. Water levels change throughout any period of flooding, and most people in the midst of a flood have more urgent duties than recording those levels. A level recorded during the flood might not represent the time when the water was highest. A level recorded some distance away from the official site might be transferred there using incorrect hydraulic assumptions.

Together, these factors offer one source of uncertainty that contribute to the differences identified between flood marks at the Rathaus tower and those linked to the present gaging network, which is the reference scale for this report. Differences continue even for recent floods, as the Rathaus marks for the floods of 2002 and 2013 are 23 cm and 11 cm too high, respectively. Similar uncertainties are likely for any of the elevations before 1954, just before the Passau gaging station began operating. The greatest known uncertainty is 60 cm, for the 1501 flood.

A second source of uncertainty is the accuracy of restoring physical marks over long time intervals. Physical marks have non-zero width, and whether the top, middle, or bottom of the mark correctly recorded the flood elevation could be forgotten over time. In addition, building materials crumble and paint fades, so either engraved or painted marks can become obscure. Despite the best efforts of many restorers, errors of perhaps 5 cm are possible.

Table 3. Flood elevation data for the Danube River at Passau.

Archive diagram (figure 3.)		Wagner table of 27.02.2008				This report		
High Water Scale on the Rathaus tower		Highwater levels in Passau				At the Rathaus tower		
Existing markings	Photo (from archive)	Elevation	Danube River at Passau		Rathaus Approx. elevation, m	Date	Elevation, m	Source
			Gage height, cm	Elevation, m				
1558		299.09						
0.13	1501	298.96	1351	299.75	299.48	15.08.1501	299.48	A
0.09	1595	298.87				03.06.2013 1558	299.27	B
0.56	1954	298.87				11.03.1595	299.00	C
0.56	1954	298.87				10.07.1954	298.78	D
0.08	1787	298.31				10.07.1954	298.58	D
0.06	1862	298.25				30.10.1787	298.22	D
0.28	1899	297.97				02.02.1862	298.14	D
0.35	1845	297.62				15.09.1899	297.86	D
0.73	1895	297.62				31.03.1845	297.51	C
0.31	1920	296.89	1081	297.27	297.15	04.08.1895	297.51	D
0.14	1883	296.58				13.08.2002	297.15	A
0.22	1897	296.44				08.09.1920	296.77	D
0.13	Match point	296.22				1.1883	296.46	C
0.38	Cove molding	295.71				8.1897	296.32	C
	Vertical reference point	295.71				Top of cove	296.10	C
	Cobblestone pavement	295.23				Reference Pavement	295.59 295.11	C C

Source notes--A: from 2008 table; B: from Belz and others (2013) compared to 1954 value; C: from Archive diagram photo, adjusted to 1986 measurements; D: from 1986 measurements.

The accuracy of converting numerical data to changing units of measurement is a third possible source of uncertainty. Current water level data at Passau and all water levels in this report are in units of meters (m) and centimeters (cm), but early water levels were recorded in units of an elle (Claudia Veit, archivist, City of Passau, written communication, 20 September 2012). The present International System of Units (SI) developed from a system established in France in 1800 and gradually adopted throughout the world after a multinational treaty in 1875. Length measurements in earlier systems commonly derived from the human body sizes of a thumb, a foot, a forearm, or a pace, which typically had different sizes in different countries, cities, and centuries. (http://en.wikipedia.org/wiki/Metric_system, <http://en.wikipedia.org/wiki/Ell>, [http://de.wikipedia.org/wiki/Elle_\(Einheit\)](http://de.wikipedia.org/wiki/Elle_(Einheit))). Numerical elevation data are measured above some defined zero elevation, and that reference elevation might change over time. The errors of flood elevations converted by city authorities to SI units and the present reference elevation, however, are safely assumed to be less than 5 cm.

How Complete is the Data Series?

For this report, the flood elevation series shown in table 3 is assumed to be complete above elevation 297.15 (the 2002 flood peak). Smaller floods, however, similar in magnitude to those of 1883, 1897, and 1920, probably occurred several times since 1501 but were not displayed on the Rathaus tower after 1920.

Table 4: Observed intervals between floods displayed on the Rathaus tower at Passau.

Flood date	Years since previous flood		
	All known elevations	Elevations greater than 297.1 m ¹	Elevations greater than 298.2 m ²
1501	--	--	--
1558	57	57	57
1595	37	37	37
1787	192	192	192
1845	58	58	--
1862	17	17	--
1883	21	--	--
1895	12	33	--
1897	2	--	--
1899	2	4	--
1920	21	--	--
1954	34	55	167
2002	48	48	--
2013	11	11	59

¹ Estimated 50-year flood elevation. ² Estimated 100-year flood elevation.

The flood elevation data for Passau show three events between 1501 and 1595, but no others until 1787 (192 years, table 4, figure 5). Since 1787, the maximum intervals between floods recorded on the tower were 58 years (1787-1845) and 48 years (1954-2002). Did no large floods occur between 1595 and 1787, were large floods simply not recorded, or were some records lost in the major fire that destroyed much of Passau in 1662 (<http://en.wikipedia.org/wiki/Passau>)?

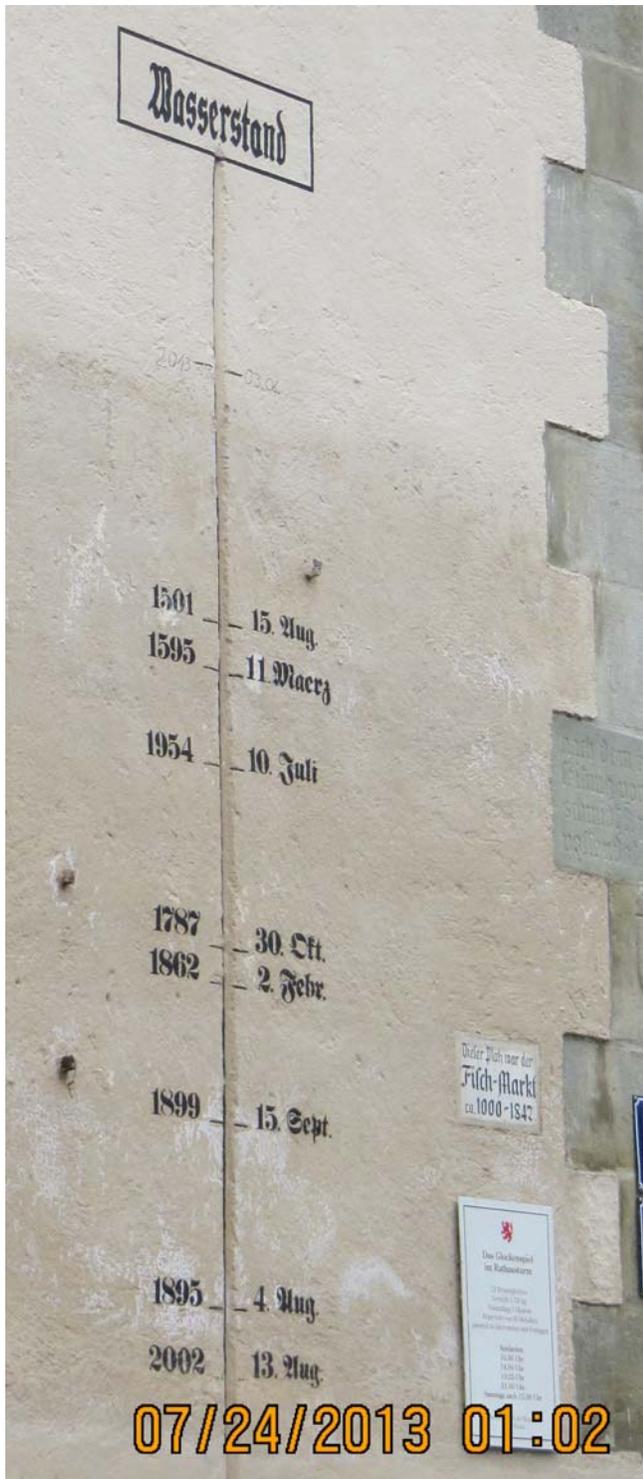
If the data series is complete for events greater than the smallest on display (1897), a frequency analysis for return periods of 50 to 125 years is simple. For the 512 years since the 1501 event, the fourth highest event (1954) represents an average return period of about 125 years, the fifth highest (1787) represents about 100 years, and the tenth highest (2002) represents about 50 years (table 5).

If that simple analysis is correct, the annual probability of an event equal or greater than 2002 is 2 percent, and the distribution of those events for any length of observational record can be calculated from the binomial statistical distribution. The cumulative distribution function for 100 trials of individual probability 2 percent shows the probability of zero 50-year floods in a century is 13 percent and the probability of at least 4 such events is 14 percent. For consecutive 100-year periods after August 1501, however, the record includes 2, 0, 1, 4, and 1 such events. Thus the zero events in the 1600's and the 4 events in the 1800's are both somewhat unlikely. Similar calculations show the probability of 3 or fewer 50-year floods in 300 years, as the record shows for 1502-1801, is only 15 percent. The probability of 6 or more 50-year floods in 200 years, as the record shows for 1811-2010, is 21 percent. Again, both results are somewhat unlikely, but not convincingly so. Thus it would not be surprising if a few other floods during 1502-1845 reached elevations greater than that of 2002, but equally, it would not be too surprising that the record is complete.

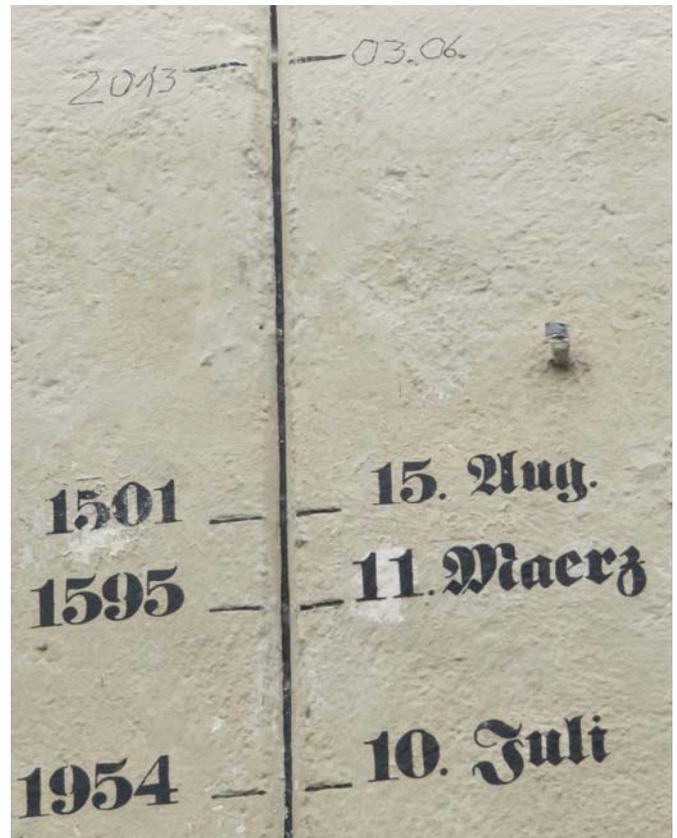
A similar analysis for the smaller events in the displayed record, however, leads to a different conclusion. The probability of observing zero floods of 40-year recurrence interval, similar to 1883 and 1897, during 150 years is just 2 percent, but the displayed record shows none during 1600-1750. The probability of not more than one 40-year flood during 200 years is 4 percent, but the displayed record shows just that for 1600-1800. It seems more likely that some smaller floods are missing from the record.

Figure 4: Photographs of the Passau high water scale on 24 July 2013.

a. Complete scale



b. Detail view



[Courtesy of Ruth Burgess. Time imprint is Pacific time; these photographs were taken about 10:00 AM local time.]

Figure 5: Flood elevations and observed intervals between floods at Passau.

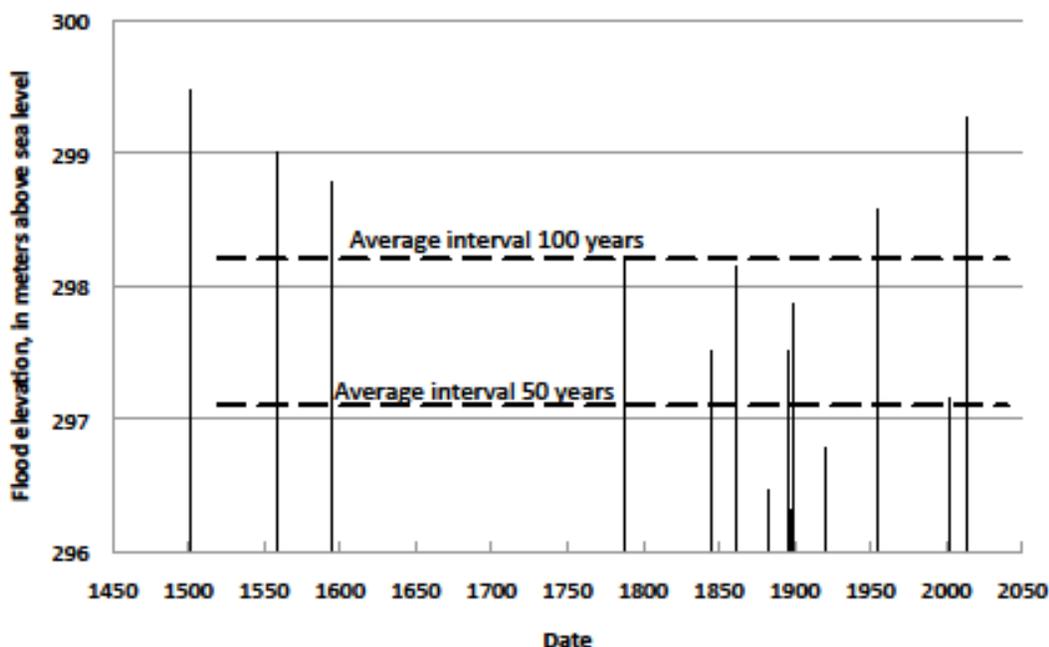


Table 5: Average flood recurrence intervals at Passau estimated from ranks of flood elevations displayed on the Rathaus tower.

Date	Elevation, meters	Rank	Estimated recurrence interval, years ¹
1501	299.48	--	--
2013	299.27	1	512
1558	299.00	2	256
1595	298.78	3	171
1954	298.58	4	128
1787	298.22	5	102
1862	298.14	6	85
1899	297.86	7	73
1845	297.51	8	64
1895	297.51	9	57
2002	297.15	10	51
1920	296.77	11	47 ²
1883	296.46	12	43 ²
1897	296.32	13	39 ²

¹ Estimated as 512 years divided by rank number. ² Value is too large, because the record for floods lower than 297 m is probably incomplete before 1845.

The flood years identified by Mühldorfer (1990, table 1) also suggest that some floods that reached the tower were simply never marked before systematic observations began in Bavaria in 1821 (Wüllner and Vogelbacher, 2004, p. 56). The 19 identified flood years between 1820 and 1990 imply the later group includes most events with recurrence intervals greater than 10 years, while the 9 identified flood years between 1500 and 1820 suggest a minimum recurrence interval of 35 years for the earlier group (table 1). It is likely, then, that 20 or 25 events greater than a 10-year flood are missing from Mühldorfer's list between 1500 and 1820, and although many of them would have been smaller than the 1920 flood, a few could have been larger. In particular, Mühldorfer identified 1662, 1682, 1752, 1785, and 1786 as flood years, but the peak elevations are unknown.

Although the question of record completeness cannot be answered with certainty, it is reasonable to assume for this report that all floods since 1501 and greater than the flood of 2002 are included in the displayed record.

Flood Records at Melk

Melk is a small city on the Danube about 190 km downstream from Passau and 100 km upstream from Vienna (figure 1) that has been inhabited for more than 1,000 years (<http://www.melk.gv.at/>, <http://en.wikipedia.org/wiki/Melk>, <http://de.wikipedia.org/wiki/Melk>). The drainage area of the Danube near Melk is about 25 percent greater than near Passau. A gaging station operated by the Hydrographic Service of Lower Austria at Kienstock, 22 km downstream from Melk, has discharge data as early as 1862 but complete records only since 1991 (table 2, <http://www.noel.gv.at/Externeseiten/wasserstand/static/stations/207357/station.html>).

A flood elevation scale on the shipping master's house (Schiffsmeisterhaus) at Melk displays seven floods between 1501 and 2002 (figure 6a, 48°13'38" N x 15°19'40" E). A second flood scale about 700 m away at the ferry building (Fährhaus), near the landing for tourist boats, shows six floods between the same dates (figure 6b, 48°14'00" N x 15°19'43" E).

The two scales show five floods in common: August 1501 as the highest and lower floods in February 1862, September 1899, July 1954, and August 2002. The Fährhaus scale adds the flood of August 1991 distinctly lower than the other marks, although the same relative elevation would be near or below the base of the wall at the Schiffsmeisterhaus. The Schiffsmeisterhaus scale adds floods in November 1787 and August 1897.

Both scales show the 1862 and 1899 flood pair at similar elevations and the 1954 and 2002 pair also at similar elevations. The Schiffsmeisterhaus scale, however, shows both pairs in a single group, while the Fährhaus scale shows the earlier pair distinctly higher

Table 6: Estimated relative flood elevations at the Melk Schiffsmeisterhaus.

Date	Relative elevation, cm	Source
15.08.1501	247	A
01.11.1787	107	A
12.07.1954	50	A
14.08.2002	46	A
04.06.2013	46	B
17.09.1899	36	A
04.02.1862	20	A
02.08.1897	0	A

¹ Source A, scaled from figure 6a; B, estimated from gage data at Kienstock.

than the later pair. The earlier pair is in the same order (1899 above 1862) on both scales, but the later pair is in reverse order on the two scales. Each source of uncertainty mentioned in the preceding section "How accurate are the elevations?" could have contributed to the differences between the two scales.

Accurate measurements were not available for this study for either absolute or relative elevations of the Melk high-water marks. This report will use estimated relative elevations at the Schiffsmeisterhaus, because they are more numerous and less vulnerable to flood damage, as they are farther from the low-water river bank.

Relative elevations were estimated by assuming each pane of glass in the adjacent window is 30 cm square and ignoring the radial-projection distortion of the photograph (figure 6a, table 6). For the flood of 4 June 2013, gage records at Kienstock report it was 12 cm lower in elevation but 1.3 percent greater in discharge than the flood of 14 August 2002. For this report, the two floods are estimated to have had equal relative elevation at the Melk Schiffsmeisterhaus.

Flood Recurrence Intervals—Danube River at Passau

Analysis of the historical average recurrence interval of Danube River floods at Passau is straightforward once the reasonable assumption is made that the record displayed on the Rathaus tower includes all floods since 1501 that were greater than the flood of 2002. The first flood in the record (1501) serves only to mark the beginning of observations. This may seem a waste of good information, as that is also the highest flood. Including 1501, however, would require choosing some earlier date for the beginning of observations, and that choice would be entirely speculative.

On average, a flood equal to or larger than that of 2002 occurred about once every 50 years (512 years/rank 10), and one exceeding 1954 occurred about once every 125 years (figure 7, table 5). In other words, the actual 2002 flood is an estimate of a future 50-year flood, and the 1954 flood is an estimate of a future 125-year flood, if the future is like the past.

This simple analysis estimates the average historical recurrence interval of each flood as the total number of years of record divided by each rank order. Such simplicity is possible only because of the great length of the total record and the assumption it is complete above 297.1 m. For the purposes of this report it is sufficient, although more sophisticated statistical analyses would be valuable for other purposes. This report illustrates the large uncertainties of estimated flood recurrence intervals for a specific site; regional flood management planning or infrastructure design would require different analyses.

Figure 6. Photographs of the Melk high water scales on 7 June 2012.

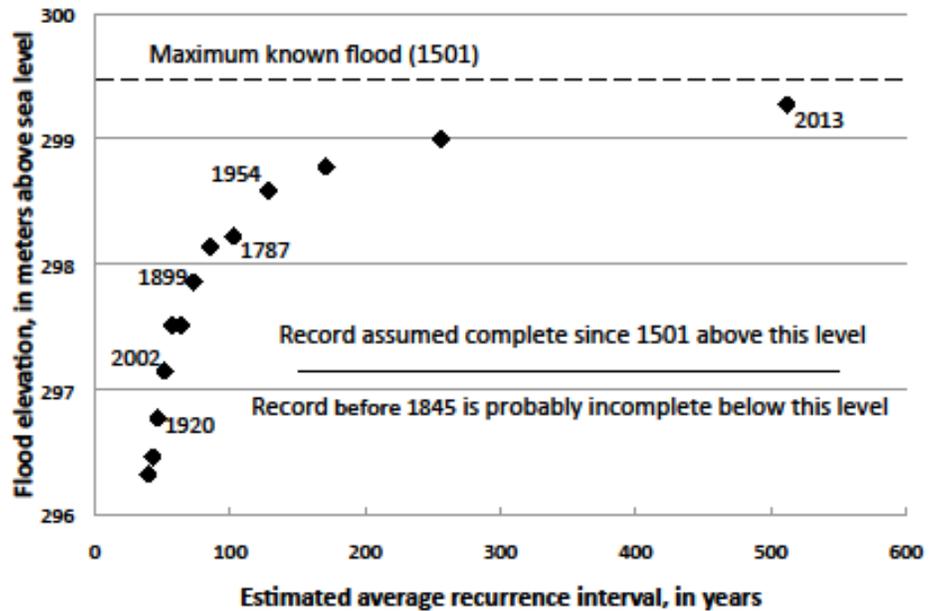
a. Schiffsmeisterhaus



b. Fährhaus



Figure 7: Flood elevations and recurrence intervals at Passau. [Data from Table 5]



The Passau record demonstrates why the words “equal to or larger than” appear in every careful definition of flood recurrence intervals. Ten floods larger than that of 2002 are in the record, so that all ten represent 50-year floods. Only two of those events, however, were closely similar to 2002 (less than 40 cm higher), while six events rose 100 to 230 cm higher.

Even when an average recurrence interval is well known, as it is at Passau for 50- and 100-year floods, the actual intervals between events are quite uncertain. For events greater than the 50-year flood, intervals ranged from 4 years to 192 years (table 4, figure 5). Three times, the interval between 50-year floods was less than one third of 50 years. Once, the interval was nearly four times as long. Similarly, among the five events greater than the 100-year flood, one actually occurred only 37 years after another (1595 after 1558). The 2002 flood (average historical recurrence interval 50 years) was followed only 11 years later by a 500-year flood. Only about half (8 of 15) of the intervals between 50- and 100-year floods were within 50 percent of the matching average historical recurrence interval, and only about a quarter (4 of 15) were within 25 percent (table 4).

For lower flood elevations, similar calculations of recurrence intervals are possible. If the Rathaus record is complete since about 1820 for elevations above 296.5 m, the recurrence interval of the 1920 flood (296.77 m) was about 25 years instead of the 47 years shown in table 5 and figure 7. Also, records from the Passau stream gages show that during 1955-2007, 11 floods rose higher than 295.1 m at the Rathaus tower, which is the pavement level (Helmut Wagner, written communication, 6 June 2012). Thus the recent average recurrence interval for floods reaching the base

of the tower was about 5 years. The actual intervals ranged from 5 months to 16 years, and about half (5 of 11) were within the range 2.5 to 7.5 years.

Does Flood Discharge Data Tell the Same Story as Elevation Data?

Flood elevations are the primary data used in this report, but most scientific analyses of flood hydrology are based on discharge, the volume of water passing a stream gage in a unit of time (such as cubic feet or cubic meters per second). Discharge is a more consistent variable for comparisons between years, upstream and downstream locations, or river basins. Elevation data can become inconsistent when river channels change over time. The Danube near Passau, however, has a water-surface slope of about 40 cm/km, a low-water channel generally 150 to 300 m wide, and stable banks that keep the high-water channel generally less than 500 m wide when the river rises as much as 10 m, which is higher than the greatest flood since 1500. These uncommon channel characteristics can be seen in databases of geographic images and topography such as Google Earth™. Therefore, the relation between elevation and discharge should be stable during floods because of “channel control” (Rantz and others, 1982, p. 10).

For the Passau-Ilzstadt gaging station (table 2), statistical analysis of flood discharge data since 1861 yields an estimated 50-year flood of 7,800 m³/s (elevation 297.15 m) and a 100-year flood of 8,800 m³/s (298.03 m; <http://www.hnd.bayern.de/>). Because of the intervening 700-m flow distance, water-surface elevations at the Rathaus tower would be expected to be about 30 cm higher, or about 297.45 m for a 50-year flood and about 298.33 for a 100-year flood.

In comparison, the 2002 flood reached elevation 297.15 m at the Rathaus, estimating the 50-year flood, and the 1787 flood reached 298.22 m, estimating the 100-year flood (table 5).

The separate 100-year estimates are quite close, but the 50-year elevation estimated from discharge data is closer to the observed floods of 1845 and 1895. That result is consistent with the possibility that a few unquantified floods earlier than 1845 might have been higher than 2002. Within the accuracy of the data and methods of this report, the estimates from discharge and elevation are consistent.

Recurrence Interval of the Latest Large Flood

The average historical recurrence interval of the most recent large flood is in fact relatively unimportant during the flood. News media focus on stories of people rescued, property damaged, and active flood defense preparations. They warn people who should evacuate, and they call volunteers to help. The largest recurrence interval estimated by anyone for any location becomes a media label for the entire flood interval, but the number on the label doesn't really matter. Instead, emergency management agencies focus on the immediate extent and short-term forecast of the flooding. They implement existing flood defense plans, mobilize resources, and allocate those resources among locations of need. The objective is to rescue people from immediate danger and minimize damage. Eventually the flood subsides and flood fighting transitions to short-term repairs and long-term rebuilding.

After the flood, many decisions must be made, by individuals and by communities acting through their governments. Each paid a price for living near the water. How much more will it cost to continue in the same place? How soon will this happen again? Is it worth the price?

An estimated recurrence interval contributes to those decisions, but the estimates are maddeningly uncertain if the flood was the largest on record or close to it. The 2013 flood at Passau is plotted at a 512-year recurrence interval in figure 7, but no other point in the graph is at all close to it along the horizontal scale. Alternative methods for the largest event in this data series would plot it at a recurrence interval as great as 1,024 years (Helsel and Hirsch, 2002, p. 23). At Passau, recurrence intervals are well defined by multiple flood events for periods of 50 to 125 years, which is sufficient for most purposes. For greater floods, the maximum known flood elevation at the site is more important than its recurrence interval. If the

future is like the past, the oldest and simplest idea is best—a future flood could rise at least as high as the previous maximum.

A reasonably accurate estimate of recurrence interval as it varied throughout the flood region becomes important for the government agencies responsible for flood protection at many locations over many years. Different questions arise at this level. Did existing flood protection structures and policies function as planned up to their design limits? Are any changes needed for projects designed in the future? Should the agency require individuals to rebuild differently than before? If so, how and when? Who should pay what share of each cost? These are difficult questions. The precise recurrence interval of a single large flood is beyond the scope of this report, and would play only a small part in answering those questions.

Recurrence Interval of the Same Flood at Different Places

The recurrence interval of a flood event varies along any river channel because of the variable intensity, extent, and timing of rainfall and snowmelt throughout the watershed. Differences in the relative elevation of separate floods between different places provide evidence of the varying recurrence interval.

At both Passau and Melk, the 1501 flood was the highest known and the 1787 flood was about 130 cm lower, but other floods were quite different between the two sites (tables 5 and 6). At Passau, the well-documented flood of 1954 was 90 cm lower than 1501, and the 2002 and 2013 floods were 233 cm and just 21 cm lower, respectively. Downstream at Melk, however, the three floods of 1954, 2002, and 2013 were within 5 cm of the same elevation and all about 200 cm lower than 1501.

The average historical recurrence intervals of the floods of 1954, 2002, and 2013 at Passau were about 125, 50, and 500 years, respectively, across an elevation range of 212 cm (table 5, figure 7). Despite their 10-fold range of recurrence intervals at Passau, these floods became nearly identical 190 km downstream at Melk, where their recurrence intervals were all about 170 years.

Clearly, the recurrence intervals of flood events can either increase or decrease from Passau to Melk, as is true along rivers everywhere. Further analysis was not possible with the information available for this study.

Lessons to Learn

In choosing how to balance the risk and reward of living near a flood hazard, people need reliable information about the risk. Within the 500 years of flood elevation records for the Danube at Passau, some intervals as long as typical U.S. records (less than 100 years) had a distinct excess or shortage of large floods compared to the full record. In addition, climate research has identified processes that could change patterns of flooding. In some senses, the design challenge is similar to that of designing the Erie Canal 200 years ago, before scientific hydrology began. Despite presently abundant scientific information, a person trying to balance risk and reward still faces uncomfortably large uncertainties.

Climate Variability and Change

Nearly all analyses of historical flood information to estimate future flood risk assume that future climate will be like the past. Even so, observed intervals between floods differ widely from their average. For example at Passau during the past 500 years, the intervals between 50-year floods ranged from 4 to 192 years and between 100-year floods from 37 to 192 years (table 4, figure 5). Such historical climate variations are unpredictable at multi-decade time scales. A home or a bridge built to serve for the next 50 years faces a risk that a new phase of long-term climate variability will arrive sooner, and that uncertainty cannot be quantified from short historical records.

Planning and design for flood safety also face a risk that climate variability will become long-term climate change as a result of greenhouse gas emissions from the use of fossil fuels (Milly and others, 2008; IPCC, 2012, 2013). The uncertainty of flood risk due to climate change also cannot yet be quantified for specific sites (Brekke and others, 2009; Kiang and others, 2011).

Together these unquantified uncertainties leave a project designer facing greater uncertainties than were routinely assumed a few decades ago. If historical records are not representative of future flood magnitudes, planning for public infrastructure projects or even individual homes in flood hazard zones will be affected by that uncertainty. Even the 500-year observational record at Passau is not sufficient to test a rigorous hypothesis of climate change, because of the large variability in the arrival time of rare floods.

Information beyond the historical flood record, however, might be able to counter these uncertainties. The fundamental physics of mass and energy movement in the global climate system are extremely complex, far beyond the single-site analysis of flood

elevations in this report. The physics-based approach, however, allows each component of the system to be considered separately, measured in laboratory or the environment, and recombined in global and regional climate models. The work involves thousands of scientists around the world, and the best summaries of the state of the science are available from the Intergovernmental Panel on Climate Change (IPCC) at <http://www.ipcc.ch/>. The IPCC began work in 1988, released a series of reports from their fifth assessment cycle during 2014, and will continue until understanding and modeling have sufficiently reduced uncertainties to become widely useful for management decisions.

Key understandings from the work of IPCC concerning future flood risk include:

- "A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events." (IPCC, 2012)
- "Changes in many extreme weather and climate events have been observed since about 1950 ... The frequency or intensity of heavy precipitation events has likely increased in North America and Europe." (IPCC, 2013)
- "Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases." (IPCC, 2013)
- "There has been some improvement in the simulation of continental-scale patterns of precipitation since [2007]. At regional scales, precipitation is not simulated as well, and the assessment is hampered by observational uncertainties." (IPCC, 2013)
- "Projected precipitation and temperature changes imply possible changes in floods, although overall there is low confidence in projections of changes in fluvial floods. Confidence is low due to limited evidence and because the causes of regional changes are complex, although there are exceptions to this statement. There is medium confidence (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments or regions." (IPCC, 2012)

Thus climate models are now useful in general but not yet able to estimate future flood magnitudes for specific rivers. Another decade of careful monitoring and research is expected to decrease the present uncertainties but is by no means guaranteed to produce fully operational tools by that time.

Planning without Reliable Risk Information

Because there is good reason to anticipate that the future will not be like the past, the historical example of the Erie Canal, a major public project designed before scientific flood records began, can be instructive. Between about 1600 and 1800, European immigration became established on the eastern coast of North America, displacing previous native peoples, and leading to the creation of the United States. Westward expansion of the United States was substantially limited, among other reasons, by the physical barrier of the Appalachian mountain chain, which extends largely uninterrupted from latitude 34° N in Alabama to at least 45° N at the border of Canada with New York, Vermont, and New Hampshire. Moving people and manufactured goods west or agricultural products east across the mountains by muscle power was slow and difficult.

The Erie Canal, completed in 1825 in western New York between the present cities of Albany and Buffalo, was the first route through the Appalachians that was capable of carrying large quantities of goods (http://en.wikipedia.org/wiki/Erie_Canal). The canal was a major factor in the early growth of the United States in the Ohio Valley and Great Lakes areas. Although competition from railroads began in a short segment as early as 1831, the original canal alignment was in service until at least 1905.

The canal route crossed at least 300 small streams (Langbein, 1976, p. 44-46). If those streams were allowed to flow uncontrolled into the canal, they could block traffic by depositing sediment in the channel, create such flow velocities in the canal as to endanger the barges, or even overflow the downhill bank of the canal. Overflow was the greatest danger, as it would erode the bank and drain an entire canal segment. The designers therefore chose to build culverts to allow the small streams to pass under the canal bed.

In 1816, the designers had essentially no information on potential flood flows from the small streams. They could measure the width of each natural stream channel above the canal, so they built culverts as wide as the channels. The height, slope, and entrance geometry of culverts are also important in how efficiently culverts convey water, but that knowledge did not develop until many decades later. Similarly, many concepts in statistics and hydrology were not yet known, so the designers were unable to associate a recurrence interval with the capacity of the culverts, and they could not calculate the annual risk to the whole system.

Every time a large flood reached an undersized culvert, the canal acted as a dam. Water rose until it overflowed one or both banks of the canal. If the downhill bank washed out, all traffic in the canal stopped, commonly for 7 to 15 days. Shipping could resume only after the bank was repaired and the canal segment refilled with water.

During the 10 years 1843-1852, the Erie Canal was out of service on average at least 5 percent of the expected 220-day annual navigation season because of damage from small streams (Langbein, 1976, p. 45). During the 25 years 1858-1882, canals in the New York state system were out of service due to breaks in the banks about 17 percent of the time; the system in those years included the Erie Canal and others whose total length was less than half that of the Erie. Both values are likely underestimates, because records were not maintained systematically.

The canal managers replaced failed culverts with larger ones, but 80 years of repairs were not enough to correct the errors of designing too small. Throughout the working life of the original canal, floods continued to damage culverts, and "repair and enlargement became surrogates for design" (Langbein, 1976, p. 46).

Design by replacing failed structures is an expensive approach to any society's future wealth and safety. In the case of the Erie Canal, the lack of knowledge of flood magnitude and frequency on small streams contributed to higher maintenance costs than expected and smaller annual operating periods than planned. Both outcomes decreased the canal benefits relative to costs.

Planning for Flood Safety

Today, 200 years after the Erie Canal was designed, communities use several complementary approaches to keep people and property safe from floods. They manage land use to balance the foreseeable risks with the benefits of occupying flood hazard zones. They design structures that must be in hazard zones to function during floods with minimal damage. They modify flow and channel conditions to reduce the area at risk. Finally, they create forecast and warning systems and plan how to respond during floods. The risk level and its uncertainty affect each component of the overall approach.

Land use management forms the foundation of U.S. national flood policy in high hazard zones, including requirements for construction and insurance (<http://www.floodsmart.gov/>). In concept, a community would assign the zone of greatest flood risk—the active river channel and its adjacent flood channel—to uses least affected by flooding, such as secondary roads or a

greenbelt for public recreation. These uses are valuable to the community during normal streamflow, can be abandoned temporarily during floods, and can be restored afterward at low cost. A second zone, at risk from larger, less common floods, would allow a wide variety of uses but be subject to design standards. Those standards might require that the main living level of a home be above a specified elevation, such as the expected elevation of a 100-year flood plus a margin for uncertainty. Other structures might be designed so that openings where flood water might enter could be sealed temporarily with sandbags. Critical community-safety facilities such as hospitals, emergency-operations centers, and police, fire, and rescue services might be built in a third zone not at risk from any imaginable flood. This approach recognizes that the best defense against floods is to seek higher ground for high-value uses. The two lower zones correspond to the U.S. regulatory classifications of the floodway and the 100-year hazard zone.

Some structures such as bridges must unavoidably be built in flood hazard areas. Some communities benefit from upstream flood control reservoirs that capture part of the water from a flood and release it later at a lower rate, thus reducing the inundated area downstream. Some communities deepen or enlarge the flood channel or build levees or floodwalls. All these structures must be designed to withstand a target flood plus an adequate margin of safety for uncertainties, balancing between present cost and future risk. Once structural flood protection is in place, communities tend to allow new investments in homes and businesses in the protected areas. If the structures fail for any reason, either from lack of maintenance or a flood greater than the design target, the damage could be greater than if the same investments had been directed to higher ground.

In addition to distributing various land uses in recognition of flood hazards and installing structural flood protection, forecast and warning systems can provide communities enough time to bring flood response plans into action. These plans would include scenarios ranging from quite minor flooding to an event greater than the uncertainty for any estimated recurrence interval. Each scenario would identify specific areas likely to flood, the available human and material resources, and priorities for action. People might be warned to withdraw temporarily from areas before they flood. Gates in flood walls could be closed. Levees might be raised with additional sandbags. Observers could monitor critical locations. Plans developed and practiced during ordinary time would be reviewed and implemented during flood time.

A recognition of the unquantified uncertainties discussed in this report might be unsettling for all of

these approaches. If the uncertainty of future flood risk along a stream reach is larger than was assumed a few decades ago, a larger margin of safety might be needed. Even though much better information about floods throughout the United States and about construction engineering is available now than in 1816 when the Erie Canal was designed, flood protection projects could become more expensive in the future through the choice of sturdier construction or perhaps unexpected repairs after a failure. Equally, if climate variability and change reduce flood magnitudes in some regions, structures might be built unnecessarily large.

Floods and flood damage are different in each local setting. For example Passau has learned through hard experience what parcels of land are safe from floods. Near the 100-year flood level of about 298 m, a small change in recurrence interval represents a relatively large change in flood elevation (figure 7). But the city is hilly and high ground is only a short walk from the Danube. A structure above 300 m elevation would be safe from effectively all flooding, so uncertainty also is manageable. Land close to the river is used for parks, streets, and vehicle parking, and the city has a detailed flood response plan that identifies what streets will be inundated by floods at various elevations. Businesses nearest to the river are reminded to prepare for flood risk by seeing the river rise and fall each year and by the flood scale on the Rathaus wall.

In contrast in flat terrain like the U.S. Gulf Coast or California's Central Valley, a naturally flood safe elevation might be miles from the low-water river bank, far out of sight and perhaps out of mind. A property owner seeking flood safety on low ground might need to build well above ground level on expensive foundations.

Summary and Conclusions

Humans have always recorded extraordinary floods, because flood damages are so great that we try to protect against future losses. If one flood could rise so high, another could in the future. This review of long flood records on the Danube River in Europe offers several lessons that may be useful to individuals and communities in the United States.

People commonly choose to live or work in places at risk of flooding, because the benefits are greater than the costs of periodic repair. Where the choice is individual and conscious, it can be quite reasonable. Even so, when a home or business is flooded for any reason, the result is a nasty mess and a serious loss to the occupants. Assistance from community volunteers, government programs, or insurance benefits never fully restores the loss.

Most areas where serious floods can occur in the United States have been mapped consistently, in a regulatory framework that identifies zones at risk of inundation by a 100-year flood at the historical average recurrence interval. On average nationwide, those 100-year flood estimates are well sufficient for the purposes of the flood insurance program and offer reasonable estimates of future flood risk, if the future is like the past.

For an individual location, however, the uncertainties can be large. Estimates for an average recurrence interval one third of the observed record length are generally accurate, but uncertainty increases as the target recurrence interval increases. Fewer than 500 locations in the United States have observed flood records as long as 90 years, so 100-year flood estimates have large individual uncertainties for most stream reaches. For the largest recorded flood at any specific location, or any potentially larger event, the recurrence interval always is poorly known.

During a time of flooding, news accounts necessarily simplify the story by reporting the greatest damage and largest recurrence interval estimated at any location. The public can easily and incorrectly assume that recurrence interval applies to the entire flood area.

In addition, the actual intervals between large floods are commonly much different than the historical average intervals. At Passau, only half of the intervals between 50- and 100-year floods since 1501 were within 50 percent of the nominal average interval. Flood events greater than the 50-year flood occurred at intervals of 4 to 192 years, and the 50-year flood of 2002 was followed only 11 years later by a 500-year flood. Similarly, the intervals between 5-year floods since 1955 ranged from 5 months to 16 years, and only half were within 2.5 to 7.5 years.

The recurrence interval of a flood event varies—either increasing or decreasing—along any river channel because of the variable intensity, extent, and timing of rainfall and snowmelt throughout the watershed. The three largest floods at Passau in the past century had recurrence intervals of 50 to 500 years and peak elevations that differed by more than 200 cm. Despite that 10-fold range of recurrence intervals, the same floods became nearly identical 190 km downstream at Melk, where the recurrence intervals were all about 170 years and the peak elevations were all within 5 cm.

Predicting future flood risk from past flood data assumes the future will be like the past. Abundant evidence shows that climate variability and change will bring a future unlike the past, but how much flood risk will change is unknown. It is an unquantified uncertainty. Much better information about floods throughout the United States and about construction engineering is available now than in 1816 when the

Erie Canal was designed. Yet because we can no longer be confident that future flood climate will be like the past, project designers face larger, unquantified uncertainties than were assumed a few decades ago. As a result, engineering projects intended to protect from or withstand flooding could become more expensive in the future, because they might need larger safety margins in design and perhaps unexpected repairs after failures.

Because the uncertainties of future flooding are so great, communities commonly struggle to balance the interests of present property owners, who seek to profit by building on land that might flood, with the interests of future property owners or occupants who might be harmed by flooding. Community decisions are hard when benefits and risks flow to different people at different times, yet the best defense against floods is to choose higher ground for high-value uses.

You pay a price to live here, but it's worth it. Creating that balance between risk and reward is an individual decision. People enjoy the benefits of living close to water, and flood hazards often accompany those benefits. When people recognize the full price of living near a flood hazard, they are more likely to make their choice consciously and responsibly.

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