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The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods

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Abstract. The June 2013 flood in the Upper Danube Basin was one of the largest floods in the past two centuries. An atmospheric blocking situation produced precipitation exceeding 300 mm over four days at the northern rim of the Alps. The high precipitation, along with high antecedent soil moisture, gave rise to extreme flood discharges in a number of tributaries including the Tiroler Ache, Saalach, Salzach and Inn. Runoff coefficients ranged from 0.2 in the Bavarian lowlands to 0.6 in the Alpine areas in Austria. Snowfall at high altitudes (above about 1600 m a.s.l.) reduced the runoff volume produced. Precipitation was distributed over two blocks separated by a few hours, which resulted in a single peak, long-duration flood wave at the Inn and Danube. At the confluence of the Bavarian Danube and the Inn, the small time lag between the two flood waves exacerbated the downstream flood at the Danube. Because of the long duration and less inundation, there was less flood peak attenuation along the Austrian Danube reach than for the August 2002 flood. Maximum flood discharges of the Danube at Vienna were about 11 000 m^3 s^{-1}, as compared to 10 300, 9600 and 10 500 m^3 s^{-1} in 2002, 1954 and 1899, respectively. This paper reviews the meteorological and hydrological characteristics of the event as compared to the 2002, 1954 and 1899 floods, and discusses the implications for hydrological research and flood risk management.

1 Introduction

In June 2013 a major flood struck the Upper Danube Basin causing heavy damage along the Danube and numerous tributaries. The city centre of Passau (at the confluence of the Danube, Inn and Ilz) experienced flood levels that were similar to the highest recorded flood in 1501. Extraordinary flood discharges were recorded along the Saalach and Tiroler Ache at the Austrian–Bavarian border. The flood discharge of the Danube at Vienna exceeded those observed in the past two centuries.

The June 2013 flood comes at a time with an amazing history of recent large floods. In August 2005, the Danube tributaries in western Tyrol and the south of Bavaria were flooded through extensive precipitation and high antecedent soil moisture (BLU, 2006). In August 2002, a major flood hit the entire Upper Danube Basin. Damage was most severe at the northern tributaries of the Austrian Danube at the Czech border, in particular the Aist and Kamp rivers. At the Kamp, flood discharges were almost three times the largest flood in the century before (Gutknecht et al., 2002). Flooding was extensive along the entire Austrian Danube which resulted in the use of the term "century flood". The preceding decades were relatively flood-poor at the Danube aside from more minor floods in 1991, 1966 and 1965; however a very large flood occurred in July 1954 with major damage along the entire Upper Danube. Again, a couple of decades with almost no floods preceded. The flood of September 1899, then, was the largest measured flood along the Danube with 48 h precipitation totals exceeding 200 mm over an area of 1000 km^2 (Kresser, 1957). Major floods occurred in August 1897, February 1862 and October 1787 with a long record of previous events (Kresser, 1957; Pekarová et al., 2013).

The aim of this paper is to analyse the causal factors of the June 2013 flood including the atmospheric situation, runoff generation and the propagation of the flood wave along the Danube and tributaries. Given the extraordinary nature of the 2013 flood, the paper also compares this flood with the largest Upper Danube floods in the past two centuries, i.e. the floods in August 2002, July 1954 and September 1899.

Fig. 1. The Upper Danube Basin upstream of Wildungsmauer. Red circles indicate stream gauges used in this paper. Black circles indicate the cities of Vienna and Passau. For catchment areas and mean elevations of the catchments see Appendix A.

2   The Upper Danube Basin

The Upper Danube Basin consists of two main subcatchments, the Bavarian Danube and the Inn. The Bavarian Danube catchment in the northwest comprises lowlands with diverse geology. Quaternary and Tertiary deposits prevail, which are highly permeable and provide large subsurface storage in porous aquifers, and there is also karst in the northwest. Some of the tributaries, such as the Lech and Isar, originate from the Alps. Elevations range from 310 to 3000 m a.s.l. Mean annual precipitation ranges from 650 to more than 2000 mm yr^{-1}, resulting in mean annual runoff depths from 100 to 1500 mm yr^{-1} (BMU, 2003). The Inn catchment, further in the south, drains a large part of the Austrian Alps. An important tributary is the Salzach. Geologically, the Inn catchment mainly consists of the northern Calcareous Alps, the Palaeozoic Greywacke zone further in the south and the Crystalline zone along the ridge of the eastern Alps (Janoschek and Matura, 1980). Elevations range from 310 to 3800 m. Mean annual precipitation ranges from 600 to more than 2000 mm yr^{-1}, resulting in mean annual runoff depths from 100 to 1600 mm yr^{-1} (Parajka et al., 2007; Nester et al., 2011).

The Bavarian Danube and the Inn join at Passau. Downstream of the confluence, along the Austrian reach of the Danube, southern tributaries from the high rainfall areas in the Calcareous Alps include the Traun, Enns and Ybbs. The northern tributaries from the lower rainfall areas with mainly

granitic geology include the Aist and Kamp. Flood protection levees have been built along many tributaries and the Danube itself during the 19th and 20th century. The total catchment area of the Danube at Wildungsmauer downstream of Vienna is 104 000 km^2. Figure 1 shows the catchments discussed in this paper, and Appendix A gives their main characteristics.

3   Large-scale atmospheric conditions

The 2013 flood was produced by an atmospheric situation that is typical of floods in the Upper Danube. In the second half of May 2013 the planetary waves of the large-scale atmospheric flow regime in the Northern Hemisphere exhibited stationary behaviour as the mean eastward zonal flow decelerated and no longer exceeded the westward propagation of the Rossby waves produced by the latitude-varying Coriolis effect (Rossby, 1939; Holton, 2004). The stationary nature of the systems is illustrated by the five-day moving averages of the geopotential height centred on 26 May and 30 May 2013 in Fig. 2. The shapes of the system centres in Fig. 2 are circular or near-circular, indicating that these centres have barely moved during the five-day averaging periods. The persistence is further highlighted by the similarity of the two patterns. Figure 2 shows the situation at 1000 hPa; standing waves were also observed at 500 hPa. The large-scale stationary flow regime led to the blocking of a number of synoptic systems including the Azores anticyclone, which
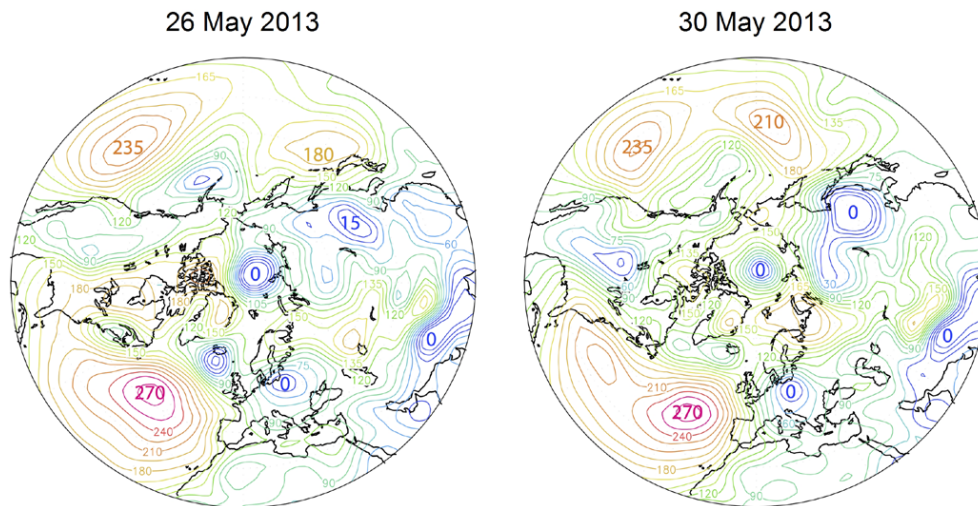
26 May 2013   30 May 2013

Fig. 2. Geopotential height fields (in meter) at 1000 hPa of the Northern Hemisphere for latitudes above 20 degrees. Five-day moving averages, centred on 26 May and 30 May 2013. The geopotential height difference between consecutive isolines is 15 m. Based on the NCEP-NCAR Reanalysis data sets (Kistler et al., 2001).

extended over a particularly vast expanse of the North Atlantic, and the Siberian anticyclone, which extended southwest of its usual position, blocking the eastward progression of the central European low. The moisture brought from the northwestern Atlantic caused rainfall in the Upper Danube Basin from 18 to 27 May. As the system positioned itself over the Alpine area, its cyclonic, anticlockwise rotation and spatial extent allowed it to collect additional moisture from the Mediterranean, feeding in particular from local depressions in the Ligurian and Adriatic seas (Fig. 3), and advecting that additional moisture cyclonically into central Europe. This regional cyclonic track is known in central Europe as "Vb", after van Bebber (1891). When the cyclonically advected air mass reached the northern fringe of the eastern Alps, persistent, heavy precipitation ensued, lasting from 30 May to 4 June 2013.

The atmospheric situation of the August 2002 flood event was similar in that the Northern Hemisphere exhibited stationarity, though not in such a pronounced way as in 2013. During the first week of August a strong synoptic depression was positioned over southern Britain and the Low Countries, bringing Atlantic and North Sea moisture into northwestern and central Europe, sweeping the region with heavy rain during the period 6–7 August. Then, the depression progressed on a southeast track, causing a break in rainfall of about three days, and settled in central Europe. The easterly progress was blocked by a high pressure swath from Scandinavia to the Caspian Sea akin to the standing high pressure over western Russia in 2013. The persistence and extent of the central European depression during the second week of August allowed cyclonic circulation to extend as far south as the Ligurian and Adriatic seas (Vb situation), again advecting air mass in an arc to the north, resulting in heavy precipitation from 7

to 11 August. However, relative to 2013 the rainfall patterns were further to the east due to the position and extent of the low pressure system, advecting Mediterranean moisture in a more pronounced Vb trajectory (namely from the Ligurian sea to the Vienna Basin).

The situation of the July 1954 flood, again, was characterised by a large-scale stationary situation with a blocked Azorean high that extended abnormally north which brought arctic moisture into northwestern Europe, causing a temperature drop and precipitation in the Alps with snowfall at elevations above 800 m on 7 July. The stationarity of the large-scale situation led not just to a large-scale blocking (as in 2013) but also to a detachment of a low pressure system from the upper tropospheric flow over the Alps, leading to substantial precipitation on 8 and 9 July.

The situation in September 1899 was quite different from those in 2013, 2002 and 1954 as there was no large-scale atmospheric stationarity. In early September, the north Atlantic anticyclone extended far to the north thus bringing moisture into Europe from the northwest. However, unlike in the other years, there was a strong surface depression in the Baltic area that brought additional moisture from the north as well. A low pressure system formed and positioned itself over the Balkan, merging with another system from the southern Adriatic. This produced an exceptionally large low pressure system extending from North Africa to the Baltic and from the western Alps to the Black Sea. Heavy precipitation ensued from 9 to 11 September. The very large spatial extent of this low pressure system gathered additional moisture from a vast expanse of the Mediterranean and the Baltic. The strong pressure gradient over the Alps (Fig. 3) led to strong currents and updraft, triggering excessive precipitation at the northern fringe of the Alps on 12 and 13 September. Note that
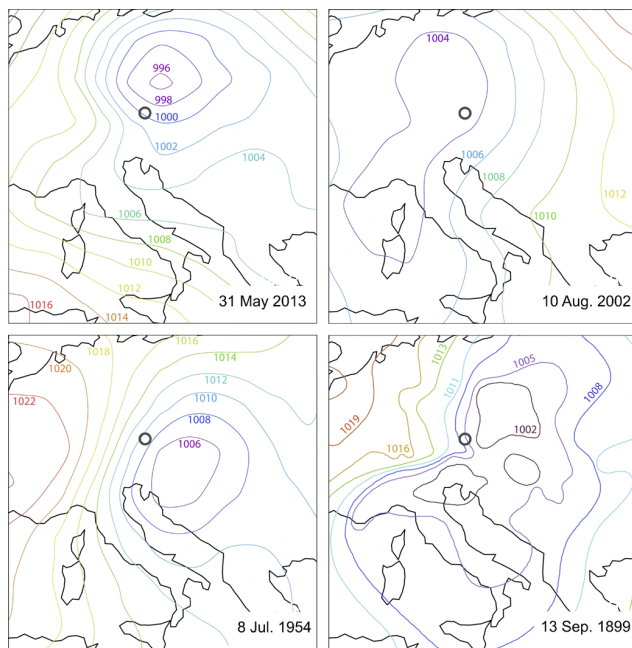
Fig. 3. Sea level pressure (hPa) in central Europe on 31 May 2013 (00:00), 10 August 2002 (12:00), 8 July 1954 (00:00), 13 September 1899 (06:00) (all times in UTC). 2013, 2002 and 1954 are based on the NCEP-NCAR Reanalysis, while 1899 is from Lauda (1900). Circles indicate location of Passau. Times have been chosen as to be most relevant for the precipitation production.

the pressure map of Lauda (1900) is based on more than 100 stations in Europe, so it shows considerable spatial detail.

4　Local meteorological conditions (precipitation and snow)

4.1　Regional precipitation patterns of the 2013 flood

Climatologically, May 2013 was one of the three wettest months of May in the past 150 yr in the Upper Danube Basin. The north of the catchment was particularly wet at the end of the month. Regensburg (near the Schwabelweis gauge in Fig. 1), for example, had 139 mm of precipitation in May 2013 as compared to the long-term May mean of 68 mm (period 1976–2011). Lower than average air temperatures resulted in low evaporation rates. The end-of-May soil moisture exceeded all end-of-May values over the period 1962 to 2012 considered in the simulations of BfG (2013) that were conducted as a function of climate variables and soil characteristics. Also, ground water levels were particularly high as indicated by numerous piezometers in the region. Further in the south, the soils were still relatively wet, although the situation was less extreme. Lofer (near the Weißbach gauge in Fig. 1), for example, had 209 mm of precipitation in May 2013 as compared to the long-term May mean of

140 mm. This means that at the beginning of the event, the soils were wet throughout the Upper Danube Basin, although there was a pronounced north–south gradient with higher soil moisture in the north, and lower soil moisture in the south.

Heavy precipitation started on 29 May in the northern part of the Bavarian Danube catchment around the city of Regensburg. From 29 May to 4 June precipitation totals of 95 mm were observed in Regensburg, 94 mm in Straubing, and 112 mm at Großer Arber to the east of Regensburg. In the southern part of the Bavarian Danube catchment and the Inn catchment, heavy precipitation started on 30 May and lasted until 2 June 2013, with smaller intensities on 3 and 4 June. From 29 May to 4 June precipitation totals of 232 mm were observed in Lofer, 244 mm in Kössen (25 km northwest of Lofer) and 270 mm in Samerberg (40 km northwest of Lofer) indicating heavy precipitation over a substantial area. Figure 4 (top left) shows the spatial pattern of precipitation for a period of seven days (29 May to 4 June, 2013). As indicated in the figure, precipitation was highest along the northern ridge of the Alps in Austria (Tirol, Salzburg and Upper Austria) and there was also very significant precipitation further in the north. Precipitation interpolated between the rain gauges based on weather radar exceeded 300 mm during this time period (Fig. 4).

As an example, Fig. 5 shows the evolution of catchment precipitation during May and the first days of June 2013 for the Weißbach catchment, a tributary to the Salzach (Fig. 1) just 10 km south of Lofer. The catchment was selected because of its large precipitation totals. Catchment precipitation was estimated from the gridded data as in Fig. 4. In this catchment, May 2013 precipitation was 184 mm, and the event precipitation from 30 May to 2 June was an additional 175 mm. The event consisted of two main precipitation blocks separated by a few hours of no or lower intensity rain. These two rain blocks were apparent over most of the Upper Danube Basin.

Air temperatures in the first three weeks of May were somewhat lower than the long-term average in the Upper Danube Basin. On 20 May, air temperatures started to decrease but recovered a few days later. A significant drop in air temperatures occurred on 29 May. Because of this, there was significant snowfall at the high-elevation stations in the Alps. The snow depths at Enzingerboden station (1480 m a.s.l., 40 km south of Weißbach) on the mornings of 30 and 31 May were 5 and 7 cm, respectively. On 31 May air temperatures increased again, which melted the snow below, approximately, 1800 m a.s.l. The snow depths at the Rudolfshütte station (2317 m a.s.l., near Enzingerboden) from 30 May to 2 June were 95, 120, 130, 190 cm, respectively.

The bottom panel of Fig. 5 shows the catchment mean air temperature (dark red line) of the Weißbach catchment. The figure indicates that during the event, on average in the catchment, the temperatures were barely above zero. The high-elevation temperatures dropped significantly below zero. The Loferer Alm temperatures (1623 m a.s.l., orange
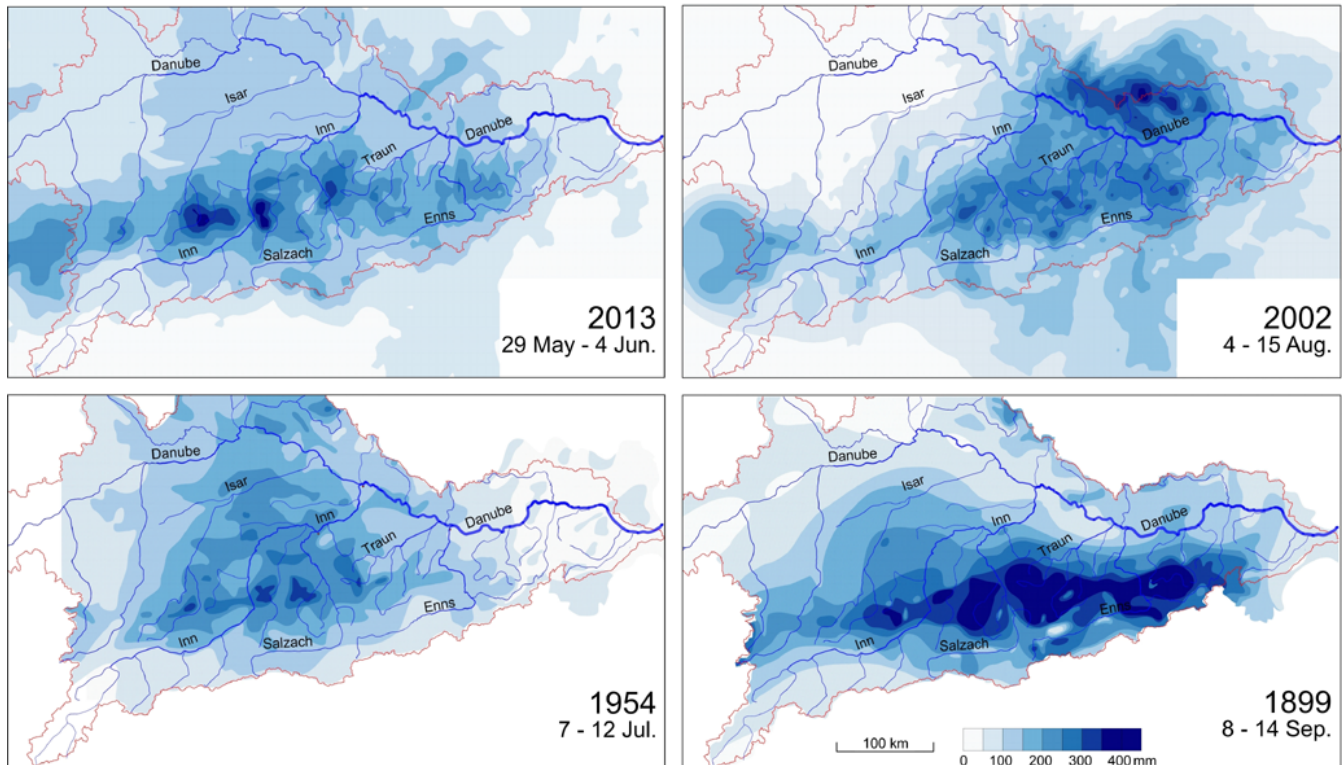
Fig. 4. Observed precipitation totals of four large flood events in the Upper Danube Basin: 29 May 00:00 to 4 June 2013 24:00; 4 August 00:00 to 15 August 2002 24:00; 7 July to 12 July 1954, and 8 September to 14 September 1899 (based on available daily records, 07:00 to 07:00). 2013 and 2002 are based on rain gauge data interpolated by the INCA method using radar (Haiden et al., 2011). 1954 and 1899 are based on rain gauge data interpolated manually from about 600 stations within the Danube Basin (HZB, 1955; Lauda, 1900). Red line indicates the Upper Danube catchment boundary above Wildungsmauer.

line) dropped to $-2\,°C$ on 30 May. Overall, 25 % of the Weißbach catchment is above an elevation of 1623 m a.s.l. indicating that a significant fraction of precipitation fell as snow, reducing the liquid precipitation available for flood runoff. However, some of the snow on the ground had melted on 1 June, adding to the available event water.

4.2 Comparison with the 2002, 1954 and 1899 floods

It is now of interest to compare the meteorological conditions of the 2013 flood with those of the previous floods. The August 2002 flood was a double event. The two rainfall peaks (7 August and 11–12 August) were separated by four days rather than a few hours as in the case of 2013. This was because of the less stationary, large-scale atmospheric situation which led to a movement of the atmospheric system between two distinct precipitation blocks. There was less precipitation in the catchment of the Bavarian Danube, but significantly more over the northern tributaries to the Austrian Danube at the Czech border such as the Kamp and the Aist (Fig. 4; Ulbrich et al., 2003). In the 620 km^2 Kamp catchment there were 200 and 115 mm of precipitation during the two events, respectively (Gutknecht et al., 2002). The first

event substantially increased the antecedent soil moisture for the second event (Komma et al., 2007). In fact, the soils were virtually saturated at the beginning of the second event which is very unusual for the sandy soils in the area. Air temperatures were rather high and the catchments most affected do not exceed 1000 m in elevation, so snow did not play a significant role during this event (Godina et al., 2003).

The three months preceding the 1954 flood were wetter than the mean. The actual event consisted of two precipitation blocks, a minor event during 1–2 July, and a more extreme block during 7–12 July. The defining feature of the event was the spatial distribution with unusually high precipitation in the north of the Upper Danube similar to, but exceeding that of the 2013 flood. During 7–12 July, 208 mm were observed in Munich and 432 mm in Jachenau, some 50 km south of Munich. At the northern fringe of the Alps, in Lofer, 257 mm of precipitation were recorded for the same period. The two-day maxima (7–8 July) at Lofer and Reichenhall were 233 and 179 mm, respectively. Both stations are within the Saalach catchment, a tributary to the Salzach. The first event increased antecedent soil moisture so that the precipitation of the second event fell on wet soils. However, substantial snow was retained in the Alpine catchments
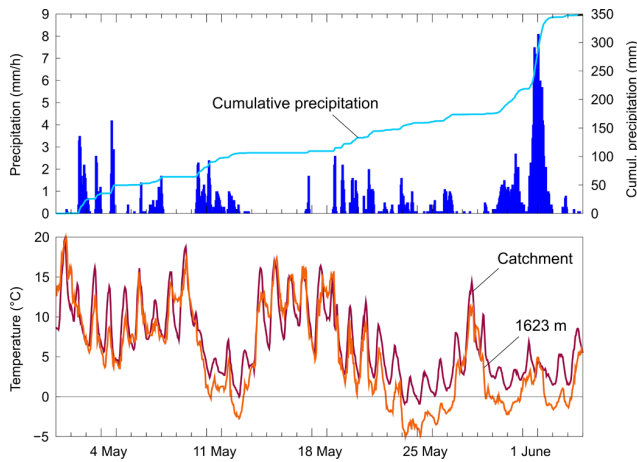
Fig. 5. (top) Catchment precipitation for the Weißbach catchment ($567 \, \text{km}^2$) in May and June 2013 (dark blue shows hourly intensities, light blue cumulative precipitation). (bottom) Catchment average temperatures for the Weißbach catchment (dark red) and air temperature at the Loferer Alm station (1623 m a.s.l., orange).

and did not contribute to flood runoff. There was snow accumulation down to 800 m a.s.l. For example, in Dienten (1200 m a.s.l., some 20 km southeast of Weißbach) snow depths increased from 20 to 77 cm on 8 July and little melt occurred on the following days (HZB, 1955).

The September 1899 flood was hydrologically quite different from the three other events. The 1898/1899 winter had been exceptionally dry with very little snow. Similarly, summer 1899 was unusually dry. August precipitation was about one-third lower than the long-term average. For example, in Waidring near Lofer, 1899 August precipitation was 114 mm as compared to the long-term mean over the previous decades of 201 mm. Because of this, subsurface stores had been depleted (as indicated by the low groundwater levels presented in Lauda, 1900) and soil moisture was low at the beginning of the event. In contrast, the event precipitation was enormous (Fig. 4). Weißbach recorded 515 mm in the period from 8 to 14 September. Not only was the total precipitation beyond any observations but also the spatial extent of the event. The 48 h precipitation totals exceeded 200 mm over an area of $1000 \, \text{km}^2$ (Kresser, 1957). Snow also played a role. Snow accumulated above about 1400 m a.s.l. which reduced the liquid water input to the event. Most of the precipitation fell in the Inn, Salzach, Traun and Enns catchments. There was a much smaller contribution from the Bavarian Danube (Lauda, 1900).

5 Runoff generation

5.1 Runoff generation of the 2013 flood

Table 1 gives the event characteristics of a number of catchments with particularly high event precipitation. The catchments drain into the Inn (Rosenheim, St. Johann, Staudach), Salzach (Weißbach, Obergäu) or directly into the Austrian Danube (Wels) (see Fig. 1) The event precipitation was of the same order of magnitude as the antecedent precipitation in May, ranging from 160 mm in the Obergäu catchment to 231 mm in the Rosenheim catchment. Because of the relatively high antecedent precipitation, and hence soil moisture, the runoff coefficients are quite large. They ranged between 0.42 and 0.56. However, these runoff coefficients are not unusually high. For comparison, the average runoff coefficients in these catchments for events with more than 50 mm precipitation are given. In Obergäu and Wels, the runoff coefficients of the 2013 event are 0.58 and 0.56 and thus very similar to the average runoff coefficients of all large events (precipitation > 50 mm) in these catchments. In Weißbach the runoff coefficient of the 2013 event is 0.42, which is somewhat lower than the averages of the large events, in spite of the relatively wet antecedent conditions. This is because part of the precipitation fell as snow and remained as snow cover until after the event in the highest parts of the catchment.

Figure 6 (left) shows the 2013 event for the Weißbach catchment in more detail. The cumulative precipitation illustrates the two precipitation blocks. The first block of 45 mm started on 30 May around midday and lasted until the evening of 31 May. The second block of 130 mm started on 1 June in the afternoon and lasted until the evening of 2 June. The first block of precipitation led to a slight increase in runoff, while the second block of precipitation increased the event runoff to a total of 74 mm. There are two reasons for the very small response to the first precipitation block. The first is the soil storage left at the beginning of the event. The second is the temperatures which were below $0 \, °\text{C}$ in one-third of the catchment (light green line in Fig. 6) so there was significant snowfall. During the second block of precipitation the percentage of the catchment with temperatures below $0 \, °\text{C}$ was lower, particularly at the beginning of the second block when it was warmer. The figure suggests that, over the entire event, around 25 % of the precipitation, or 44 mm, fell as snow and the remaining 131 mm fell as rain. If one only counts rainfall, the associated runoff coefficient is 0.56 which is more in line with the antecedent soil moisture. However, it is likely that some (but not all) of the snow that fell at the beginning of the event melted during the event. The situation in the Weißbach is typical of the Alpine high rainfall catchments during the June 2013 flood. St. Johann and Staudach (Table 1) give similar figures but somewhat higher runoff coefficients because of the lower fraction of snowfall.

In the Bavarian Danube catchment there was also substantial precipitation, albeit with a strong south–north gradient and precipitation that started earlier. Figure 6 (right) shows the cumulative event precipitation and event runoff for the Hofkirchen catchment ($45\,610 \, \text{km}^2$). Catchment precipitation was significantly lower than in the Weißbach with a total of 116 mm since the northwest of the catchment contributed less precipitation than the southern Alpine section.

Table 1. Characteristics of the June 2013 flood in small catchments in the Upper Danube Basin with particularly high event precipitation. Catchment precipitation in May (*P* May, average 1976–2011), May 2013 (*P* May 2013, 1–29 May 2013), during the event (*P* event 2013, 30 May–4 June, 2013), event runoff of 2013 flood, runoff coefficient of 2013 flood, mean runoff coefficients for events with precipitation > 50 mm, and 2013 peak runoff. For catchment locations see Fig. 1. Runoff coefficients are from Merz and Blöschl (2009) and Merz et al. (2006).

Catchment	Stream	Catchment area (km^2)	*P* May average (mm)	*P* May 2013 (mm)	*P* event 2013 (mm)	Event runoff 2013 (mm)	Runoff coefficient 2013 (–)	Mean Runoff coefficient (–)	Peak runoff 2013 ($m^3\,s^{-1}$)
Rosenheim	Mangfall	1090	106	231	228	100	0.44	0.45	530
St. Johann	Kitzbüheler Ache	330	114	210	190	96	0.50	0.38	290
Staudach	Tiroler Achen	944	112	216	226	130	0.58	0.49	950
Weißbach am Lofer	Saalach	567	114	184	175	74	0.42	0.47	470
Obergäu	Lammer	395	111	205	160	93	0.58	0.58	600
Wels	Traun	3425	103	192	187	105	0.56	0.57	1650

However, relative to previous events, the precipitation in this catchment was still enormous. At the scale of this catchment, the two precipitation blocks are still visible, but they were only separated by 12 h. The first block consisted of 45 mm, the second of 61 mm, and there was some early precipitation of 10 mm on 29 May. Temperatures were above zero in almost the entire catchment. Only 31 mm out of the 116 mm precipitation contributed to the runoff, resulting in a runoff coefficient of 0.27. This is because of the highly permeable soils and the large storage capacity in the catchment in spite of the high antecedent soil moisture. The cumulative runoff depth in Fig. 6 right (red line) indicates the substantial delay between precipitation and runoff. Essentially all the precipitation was stored in the catchment at the inception of runoff.

5.2 Comparison with previous floods

It is now of interest to put the 2013 event for those areas where rainfall was particularly large into the context of the longer-term flood history in the area. Figure 7 (left) shows the extreme value statistics for 48 h precipitation of the Lofer rain gauge located near the Weißbach stream gauge. In June 2013, the two-day precipitation was the highest since beginning of the data set in 1961. Around 173 mm of precipitation were observed in two days at this station, as compared to 122 mm during the August 2002 flood. Based on a Gumbel distribution, this precipitation total corresponds to a return period of about 70 yr. The right panel of Fig. 7 shows the extreme value statistics of the flood peaks at the Weißbach stream gauge. With a peak runoff of 480 $m^3\,s^{-1}$ the 2013 flood was the highest since beginning of the observations in 1959. The associated return period is around 100 yr. The 2002 flood peak was slightly lower, with a peak discharge of 400 $m^3\,s^{-1}$. The return period on the order of 100 yr for the June 2013 flood peak applies to a number of catchments in the area, in particular those at the Tiroler Achen und Saalach (Table 1, Fig. 1), and produced flood discharges with return periods of about 100 yr at the downstream reaches along the Salzach and Inn.

At the small catchment scale, the August 2002 flood was most severe in the Kamp catchment at the Austrian–Czech border. In the Kamp and nearby catchments, the soils are sandy and thus much more permeable than the catchments of Table 1. Because of this, the runoff coefficients are usually quite low. For the Kamp at Zwettl catchment (620 km^2) the average runoff coefficient (for event precipitation > 50 mm) is 0.20 (Merz et al., 2006). Due to the large rainfall depths of the 2002 event (200 and 115 mm from the two events) soils did become saturated, leading to runoff coefficients of 0.41 and 0.58 for the two events, respectively (Komma et al., 2007) which is almost three times the average. The resulting flood peak was 460 $m^3\,s^{-1}$ (as compared to the second largest peak of 170 $m^3\,s^{-1}$ since beginning of the record in 1896) which made the 2002 flood at the Kamp locally substantially more unusual than the 2013 flood in the Weißbach and nearby catchments (Merz and Blöschl, 2008a, b; Viglione et al., 2010, 2013).

The 1954 flood exhibited significant antecedent precipitation and a pre-event which increased antecedent soil moisture. At the Lofer station, the maximum two-day precipitation total was 233 mm (7–8 July, 1954) although a significant part of it fell as snow as there was snowfall down to 800 m a.s.l. which reduced runoff production (HZB, 1955).

Prior to the 1899 flood, subsurface storage was depleted and soils were dry. This explains that the flood response was not much bigger than those of the 1954, 2002 and 2013 floods even though the event precipitation was more than 50 % higher in many catchments. At the Weißbach station (near Lofer), the maximum two-day precipitation total was 329 mm (12–13 September 1899) and only a small fraction of it fell as snow (Lauda, 1900).
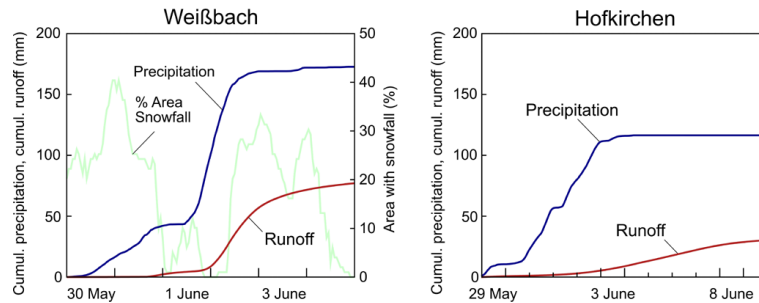
Fig. 6. Cumulative precipitation (blue lines) and cumulative runoff depths (red lines, direct runoff only) for the June 2013 flood event. Light green line in the left panel shows the catchment area with temperatures below 0 °C. (left) Weißbach catchment (567 km^2), (right) Hofkirchen catchment (45 610 km^2).
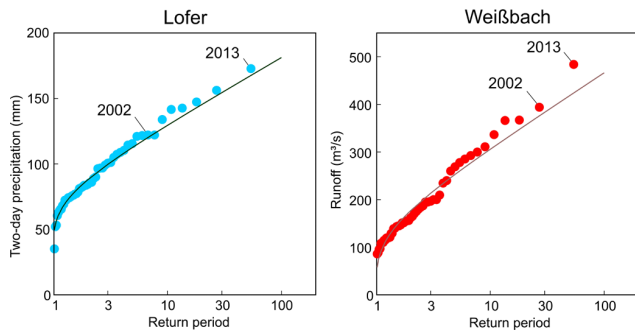

Fig. 7. (left) Statistical analysis of annual maximum precipitation (48 h totals, 07:00–07:00) for the Lofer rain gauge near Weißbach. (right) Statistical analysis of annual maximum runoff for Weißbach (567 km^2). Lines show fitted Gumbel distributions. Lofer data 1961–2013. Weißbach data 1959–2013. The 1954 and 1899 precipitation depths of 233 and 329 mm, respectively, are not included in the figure.

6 Flood wave propagation and confluence

6.1 Spatial flood hydrograph patterns of the 2013 flood

The spatio-temporal rainfall patterns of the 2013 flood, combined with differences in runoff response characteristics between the catchments (Gaál et al., 2012), produced complex patterns of runoff hydrographs within the Upper Danube Basin. Figure 8 gives an overview of the evolution of the flood with the basin.

At the Bavarian Danube in the northwest of the basin, the flood response was delayed with relatively flat peaks, similar to previous floods (e.g. 2002, 1954, 1899). This is because of the highly permeable subsurface. However, the total volume of the 2013 flood along the Bavarian Danube was exceptionally large because of the high rainfall and very high antecedent soil moisture, particular in the northern tributaries Vils, Naab and Regen. There were major contributions from the Isar and the Lech originating in the Alps where rainfall was even higher.

The Inn exhibited a much faster response as is always the case with this type of regional floods. The Upper Inn showed very little flood runoff and the flood wave built up through tributaries in Bavaria. The flood wave of the Inn at Wasserburg merged with the Salzach wave, peaking essentially at the same time, and produced a very steep wave at Schärding. There was relatively little flood retention along the Inn before the confluence but a number of small tributaries such as the Rott (280 m^3 s^{-1} peak flow associated with a return period around 50 yr) contributed to the magnitude of the flood. At Schärding the flood peaked at 15:00 on 3 June with a discharge of about 5950 m^3 s^{-1}, which represents an estimated return period of about 100 yr.

The confluence of the Inn with the Bavarian Danube at Passau resulted in a characteristic, combined shape of the flood wave at Achleiten where the fast and slow contributions of Inn and Danube are clearly visible. During the propagation of the flood wave along the Austrian Danube, it changed shape due to retention in the flood plains, which is apparent by the kink of the rising limb about a day before the peak. Inflow from southern tributaries along the Austrian reach of the Danube, including the Traun, Enns and Ybbs, gave rise to an early secondary peak, indicating that these tributaries peaked much earlier and hardly contributed to peak flows along the Danube. While the flood peaked on 2 June at 20:00 in both Wasserburg and Oberndorf, it peaked on 6 June at 05:00 in Wildungsmauer close to the Austrian–Slovak border.

6.2 Confluence at Passau of the 2013 flood and comparison with the 2002, 1954, 1899 floods

The confluence of the peaky flood wave from the Inn with the more delayed flood wave from the Bavarian Danube at Passau is a crucial element in the flood characteristics of the Upper Danube. During the 2013 flood, the inundation level in Passau was enormous (12.89 m) (BfG, 2013). It was of the same order of magnitude as the 1501 flood event (between 12.70 and 13.20 m, depending on the source, Schmidt, 2000; BfG, 2013) which is considered the highest flood in the past millennium (Kresser, 1957).
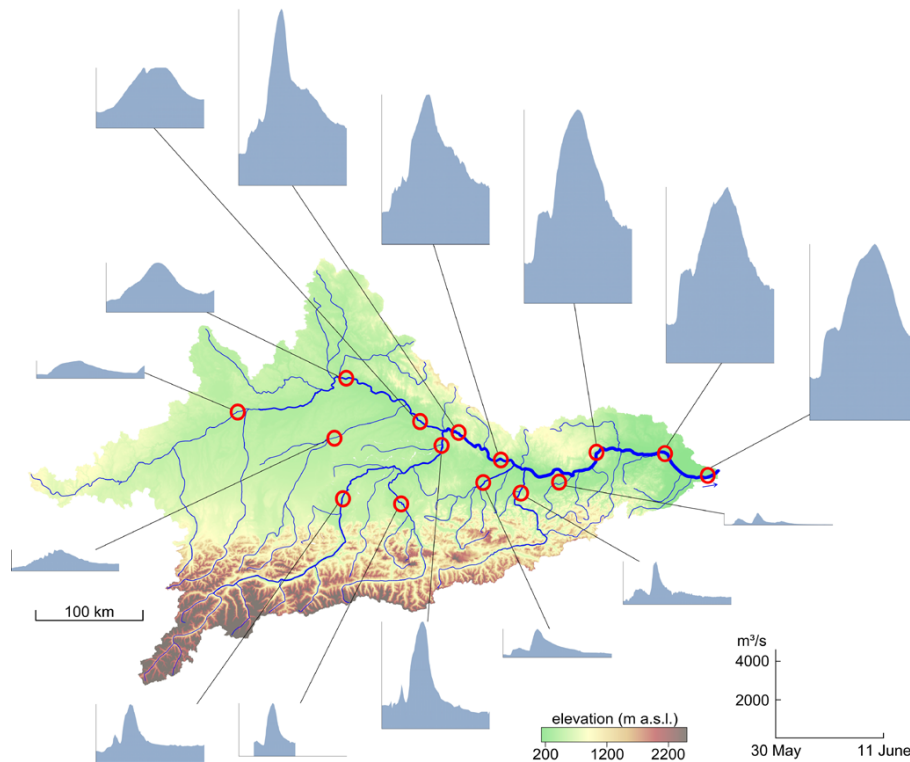
Fig. 8. Propagation of the June 2013 flood along the stream network of the Danube Basin. Red circles indicate the stream gauges as in Fig. 1. The scale shown on the bottom right relates to all hydrographs (light blue areas).

To understand the particularly large flood levels in Passau with implications downstream, Fig. 9 shows the flood hydrographs for stream gauges at the Inn and Danube just above the confluence (Schärding and Hofkirchen/Vilshofen), as well as just below the confluence (Achleiten). For the 2013 and 2002 floods the discharges are given, while for the 1954 and 1899 floods the water levels are given, since reconstruction of the complete runoff hydrograph is prone to uncertainties. It is clear that the Inn flood wave is always much faster than that from the Bavarian Danube. In 2013, the flood wave of the Bavarian Danube (at Hofkirchen) arrived somewhat earlier than usual, as compared to the Inn flood wave. This is because rainfall started a little earlier (on 29 May, rather than on 30 May, as in the Inn catchment) and because of the very high antecedent soil moisture. On 4 June, 2013, a dam along the Bavarian Danube and the Isar collapsed and caused large spatial flooding in Deggendorf, 30 km upstream of Hofkirchen. This explains the kink in the runoff hydrograph and the flat crest of the flood wave.

In terms of the confluence, the June 2013 flood was most similar to the July 1954 flood when the Bavarian Danube had similarly large flood discharges. At Hofkirchen (and the nearby Vishofen gauge) the 2013 and 1954 peaks were 3420 and 3320 $\mathrm{m^3\,s^{-1}}$, respectively. The 2013 peaks were slightly larger due to three main reasons. (i) In 2013 it was warmer than in 1954 with less snowfall, so relatively more rain was available for runoff generation; (ii) in 2013 rainfall was more concentrated along the northern fringe of the Alps where infiltration capacity is lower than in the north of the basin, where much of the rain fell in 1954; and (iii) antecedent soil moisture in the north was probably higher in 2013 than in 1954.

During the 2013 flood event, the wave from the Bavarian Danube arrived comparatively early. At the time Schärding peaked, Hofkirchen showed a discharge of 3000 $\mathrm{m^3\,s^{-1}}$ which was close to its peak discharge of 3420 $\mathrm{m^3\,s^{-1}}$. With smaller differences in the time lag between the Bavarian Danube and Inn waves as well as larger discharges in the Bavarian Danube, the resulting flood wave was significantly higher than in 1954 (10 000 $\mathrm{m^3\,s^{-1}}$ peak flow in Achleiten in 2013 as compared to 9100 $\mathrm{m^3\,s^{-1}}$ in 1954).

2002 was different in that the Bavarian Danube flood wave was more delayed, so the superposition was less efficient than in 2013 and 1954. The Inn wave was smaller too because of less rainfall in the catchment area. The 2002 flood was therefore much smaller in Passau, but received major contributions from the tributaries along the Austrian reach of the Danube (including the Kamp, Aist, Traun and Enns) as illustrated by Fig. 10.1 in Blöschl et al. (2013a). Similarly, the 1899 flood was much smaller at the Bavarian Danube because of less rainfall and dry soils. The 1899 flood was most
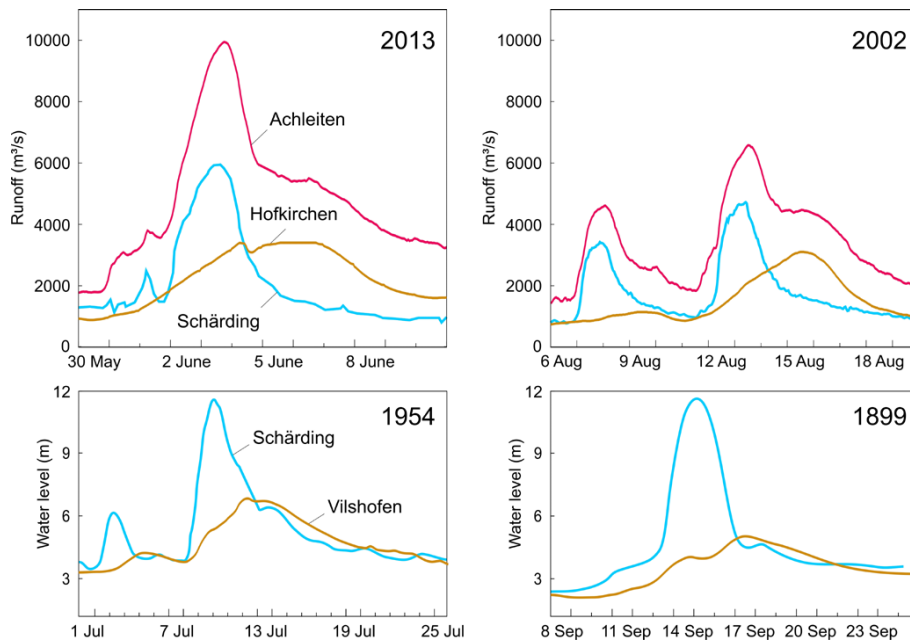
Fig. 9. (top) Runoff hydrographs for the June 2013 and August 2002 events at the confluence of the Inn (Schärding) and the Bavarian Danube (Hofkirchen). Runoff at Achleiten is the sum of Schärding and Hofkirchen plus the Ilz, a minor tributary. (bottom) Water level hydrographs for the July 1954 and September 1899 events at similar locations (Vilshofen is close to Hofkirchen). The 1954 peak discharges at Schärding and Vilshofen were 6300 and 3320 $m^3 s^{-1}$, respectively, and the 1899 peak discharges were 6400 and 2370 $m^3 s^{-1}$, respectively.

severe along the Inn, the Traun and the Enns as indicated by the rainfall distribution in Fig. 3.

6.3 Propagation of the 2013 flood along the Austrian Danube and comparison with 2002, 1954, 1899

After the confluence of the Bavarian Danube and the Inn at Passau, the 2013 flood wave travelled down the Austrian Danube, changing shape and shifting the timing. Figure 10 shows the time evolution of the peak flow from Passau to Wildungsmauer close to the Austrian–Slovak border. For this reach, the total time lag of the peak during the 2013 flood was 60 h. The celerity of the flood wave is related to two main factors, (i) the rainfall distribution and hence the contribution and timing of the tributaries, and (ii) the flood propagation of the main wave itself and the associated retention in the flood plains. The propagation of the 1954 flood was much slower than that of the other events (118 h, Fig. 10). This is because much of the rainfall occurred in the Bavarian Danube catchment (Fig. 3) with relatively minor contributions from the southern tributaries Traun and Enns, and hardly any contributions from Kamp and Ybbs. Also, there were significant inundations in the flood plains, particularly upstream and downstream of the Linz, contributing to the delay. In contrast, 2002 was the fastest event because those tributaries contributed significantly to the rising limb and peak of the flood wave, thus apparently accelerating the flood propagation, in particular the first wave (2002-1). The 2013 flood was in between 1954 and 1899 in terms of rainfall distribution,

so from that perspective one would expect celerities between 1954 and 1899, i.e. a total time lag of around 80 to 90 h. However, the wave celerity was somewhat faster than that. During the 1899 flood, a total area of 1070 km^2 was inundated along the Austrian Danube and tributaries as estimated by Lauda (1900). With an assumed average inundation depth of 2 m, this area corresponds to a total retention volume of more than 2 billion m^3. This is very significant relative to the volume of the 1899 flood (6.6 billion m^3, without base flow, Lauda, 1900), indicating that the retention effect was indeed very important during that event. As compared to 1899, the retention volume had been decreased significantly by 2013 because of flood protection levees, hydropower projects and mobile flood protection. The smaller retention volumes, and possibly the greater water depths in the reservoirs of the run-on-river power plants, have likely contributed to accelerating the flood wave, although detailed hydrodynamic studies would be needed to exactly ascertain the reasons for the changes in the wave celerities (e.g. Fischer-Antze et al., 2008). Detailed analyses of observed flood celerities at the Danube are provided in Szolgay and Danáčová (2007) and Mitkova et al. (2005).

6.4 Magnitude of the 2013 flood at the Austrian Danube and comparison with 2002, 1954, 1899

Figure 11 shows the extreme value statistics of the maximum annual floods for two stream gauges along the Austrian Danube, the Kienstock and Korneuburg gauges. Korneuburg
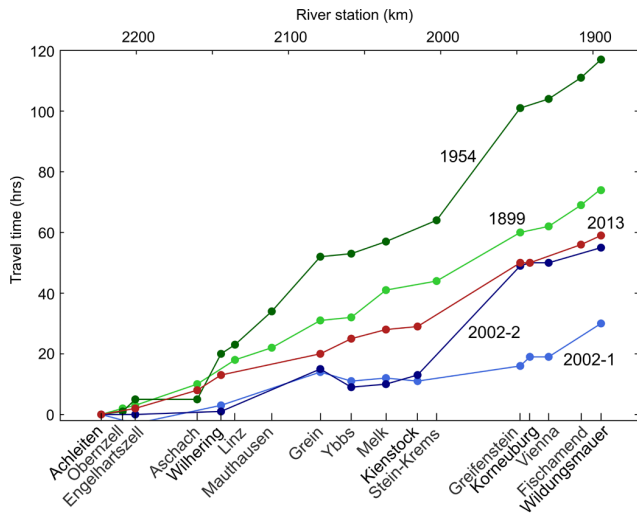
Fig. 10. Travel times of the 2013, 2002, 1954 and 1899 floods along the Austrian reach of the Danube from Achleiten near Passau to Wildungsmauer near the Slovak–Austrian border. 2002-1 and 2002-2 relate to the first and second flood waves of the 2002 event, respectively. At Passau/Achleiten the flood peaks occurred on 3 June, 2013, 18:00; 8 August, 2002, 02:00; 13 August, 2002, 12:00; 10 July, 1954, 08:00; and 15 September 1899, 10:00, which has been plotted as 0 for the five floods in the figure.

is about 12 km upstream of Vienna, while Kienstock is about 85 km upstream of Vienna. Even though the spatial distribution of precipitation, runoff generation and the spatial evolution of the 2013 and 2002 floods were different, the maximum runoff values along the Austrian Danube were quite similar. The flood runoff of both events was associated with return periods on the order of 100 yr, based on the statistical analysis. The 2013 flood runoff was clearly larger than that of the 1899 and 1954 floods.

It is interesting to compare the relative magnitudes of the peak runoff of these events between the two locations. While at Kienstock the 2013 flood runoff peak was almost identical to that of 2002, at Korneuburg the 2002 peak was significantly lower. In 2013, the peak runoff only decreased slightly along this reach (Kienstock 11 100 m³ s⁻¹, Korneuburg 11 055 m³ s⁻¹). In 2002, this decrease was much stronger (11 300 vs. 10 250 m³ s⁻¹). At first sight this is counterintuitive, as the 2002 flood had substantial inflows along the Kienstock–Korneuburg reach (in particular from the Kamp, Figs. 1, 4) while the inflows during the 2013 event were much smaller. The smaller peak attenuation is due to two main reasons. (i) Both events, 2002 and 2013, had two precipitation blocks. However, in 2013 the time period between the blocks was only a few hours, while it was four days in 2002. The 2002 event had two atmospheric rainfall producing situations with movement in between due to less atmospheric stationarity than in 2013. Because of the short interstorm period, the two precipitation blocks in 2013
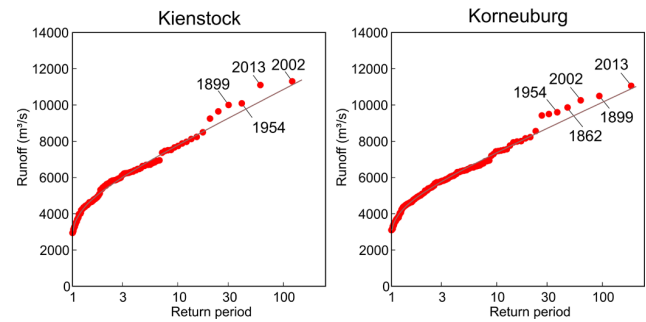

Fig. 11. Statistical analysis of annual maximum runoff for Kienstock (95 970 km², left) and Korneuburg (101 536 km², right). Lines show fitted Gumbel distributions. Kienstock data 1893–2013, Korneuburg data 1828–2013. Kienstock is a combined series with the nearby Stein–Krems gauge; Korneuburg is a combined series with the nearby Vienna gauge.

combined to a single flood wave on the Danube which exhibited a larger runoff volume than either of the two 2002 events. This is illustrated in Fig. 12 by the flood hydrographs of the 2002 and 2013 flood events at Kienstock and Korneuburg. During the 2013 flood at Kienstock, a runoff threshold of 9000 m³ s⁻¹ was exceeded during 81 h, while in 2002 the same discharge was only exceeded in 52 h, so the flood volume to be stored in the flood plains was smaller in 2002 resulting in a bigger peak reduction. (ii) Second, there were differences in the performance of the levees and the way the hydraulic structures were operated along the Danube. In the aftermath of the 2002 flood, levees had been strengthened, which resulted in relatively less inundation along the reach in 2013 as compared to 2002 possibly contributing to a smaller peak reduction. Again, detailed hydrodynamic studies would be needed to analyse the effects of individual hydraulic structures.

Overall, the flood volumes at Korneuburg (near Vienna) were enormous for all four floods. The total runoff volume of the 2013 flood from 31 May to 17 June (including base flow) was 9.5 billion m³, the volume of the 2002 flood from 11 to 26 August (second event only) was 6.5 billion m³, and the volumes of the 1954 and 1899 floods (8–27 July and 10–28 September) were 9.9 and 8.5 billion m³, respectively.

7 Lessons learnt and implications

7.1 Implication for hydrological research and design flood estimation

The June 2013 flood came at a time when the 2002 flood had still been fresh in the minds of hydrologists. The lessons learnt from the 2013 flood therefore complement those learnt from the 2002 flood. From a hydrological perspective, the analysis of the causal factors in this paper highlights the outstanding role of the *combination* of extreme factors that
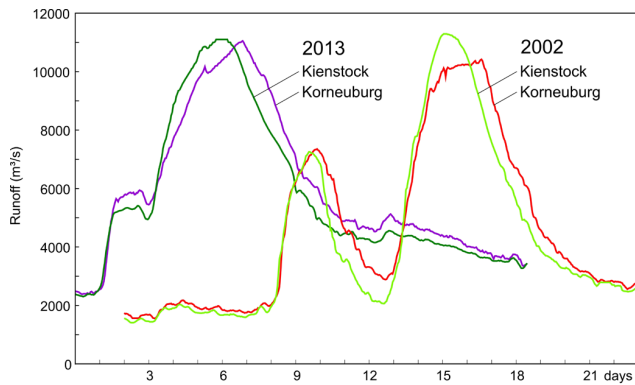
Fig. 12. Comparison of the 2013 flood (dark colours) and the 2002 flood (light colours) for the Kienstock and Korneuburg stream gauges at the Danube which are 73 km apart.

control the magnitude and characteristics of extreme floods. Indeed, the 2013 flood has had a number of characteristics that contributed to increasing its magnitude, in particular relatively high antecedent soil moisture, little shift between the flood peaks at the confluence of the Bavarian Danube and the Inn, and rainfall blocks close together resulting in a single, large volume flood wave with relatively small peak attenuation. While the important role of the combination of a number of extreme factors has been already emphasised in the past (Kresser, 1957; Gutknecht 1994), the combination of factors remains an essential concept for understanding the magnitude of large, regional floods. On the other hand, there were also factors that could have easily been more extreme. There was less total precipitation than in 1899 and, in the Alpine area, there was a significant snowfall component which retained some of the water in the catchments. Clearly, more extreme situations are possible from a hydrological perspective, albeit unlikely. Rainfall as in 1899 with high antecedent soil moisture as in 2013 would produce a significantly larger flood. This has important implications for estimating design flood values. While statistical analyses are important when estimating design flood discharges, particularly in large catchments with long flood records, it is equally important to address the problem from a process perspective and understand what combinations of factors could plausibly be expected to occur during extreme situations. This is in the spirit of flood frequency hydrology, a framework for understanding and estimating flood discharges by combining local flood data with additional types of information: temporal information on historic floods, spatial information on floods in neighbouring catchments, and causal information on the flood processes (Merz and Blöschl, 2008a, b; Viglione et al., 2013; Gaál et al., 2010). The German guidelines, for example (DWA, 2012), explicitly recommend including temporal, spatial and causal information to complement the local, systematic flood data in the analysis.

Another notable feature of the 2013 flood is that it exceeded the largest flood runoff observed in the past two centuries in many parts of the Upper Danube Basin and one may wonder whether such an extreme flood, shortly after the 2002 flood, is an indicator of increasing flood magnitudes in the Upper Danube. There are three main factors that potentially contribute to changes in regional floods related to climate, catchment processes, and the river network (Merz et al., 2012). Change in climate has attracted substantial recent discussion related to increases in rainfall extremes (Blöschl and Montanari, 2010; Kundzewic, 2012). Some indicators such as weather patterns (Petrow et al., 2009) and flood seasonality (Parajka et al., 2009, 2010) do point to changes in the atmospheric system in Europe, but the issue is far from resolved and it is not clear how to model such changes reliably (Merz et al., 2011; Peel and Blöschl, 2011). However, it seems clear that extreme floods do not arrive randomly but cluster in time into flood-poor and flood-rich periods consistent with the Hurst effect (Jain and Lall, 2001; Khaliq et al., 2006; Szolgayova et al., 2013). Changes in catchment processes include land use changes. Their effect is usually quite local as in urban floods, but less important for regional floods (Blöschl et al., 2007). Also, the importance of land use tends to decrease with the magnitude of the events (Salazar et al., 2012). Changes along the river network are more tangible. Levees have been built along the Danube and tributaries in the past two centuries, thereby reducing potential retention volumes in the flood plains (Szolgay et al., 2008). Additionally, hydraulic structures such as reservoirs of run-on-river power plants, river regulation projects and changes in stream morphology will contribute to changes in the flood propagation. An example of the latter is the stream bed degradation of the Traun River between 1899 and 1954 of about 60 cm, leading to significantly less flood inundation in 1954 as compared to 1899 at the Traun (Kresser, 1954). Also, as the flood waves change their celerities, the modified relative timings at confluences may alter the characteristics of the flood. Again, a process-based analysis is needed that accounts for the interplay of these effects. In the FloodChange project these changes are analysed in detail on the basis of the flood frequency hydrology concept of combining local flood data with historic floods, and spatial and causal flood information (Merz and Blöschl, 2008a).

7.2 Implications for flood risk management

While there was significant damage during the 2013 flood there is no doubt that, overall, the flood protection measures put into place throughout the past two centuries have vastly reduced the damage relative to a scenario without protection. Historically, much of the mitigation activities have focused on structural measures such as levees, but there is an increasing awareness that a number of flood management measures are needed to complement each other (Merz et al., 2010a, b; Sayers et al., 2013). These include structural measures such

as levees for flood protection and construction of polders for flood retention, and non-structural measures such as spatial planning and increasing the preparedness of local citizens. Retaining water in polders and retention basins is always useful as, even for extreme flooding, flood attenuation will occur with positive effects downstream. The drawback is that a lot of area is needed for flood retention to be effective for large rivers such as the Danube, as the flood peak reduction is a direct function of the available storage volume relative to the flood volume. In highly populated areas it is difficult to make sufficiently large areas available, so levees will continue to play a central role in flood management. However, levees may exacerbate flood risk downstream. Integrated flood risk management therefore considers the river basin as a whole as stipulated by the EU flood risk directive (EU, 2007).

Local protection of buildings, along with raising flood risk awareness and preparedness of local citizens, may be highly effective to complement the other measures. For these, and other flood event management measures such as early evacuation and reliable warning systems driven by hydrological forecast models are needed. The maximum water level of the 2013 flood was in fact predicted very well along the Austrian Danube for lead times between 24 and 48 h (depending on the location), although the wave celerity was overestimated (Blöschl et al., 2013c). While large-scale meteorological models and satellites provide important inputs, in particular on future precipitation, capturing the local hydrological situation is essential for accurately modelling floods (Blöschl, 2008). Increasingly longer lead times are expected from warning agencies, which requires the estimation of forecast uncertainties to quantify the confidence one has in the predictions (Cloke and Pappenberger, 2009; Laurent et al., 2010; Komma et al., 2008; Nester et al., 2012). However, communicating these uncertainties remains a challenge. Visualisation tools are one potential avenue towards assisting the communication (Ribicic et al., 2013; Hlavcová et al., 2005).

These flood management activities are important for all floods that exceed bank full discharge and potentially produce damage. Extreme floods, exceeding the June 2013 flood in magnitude, however, require special attention. A flood produced by the 1899 rainfall with 2013 antecedent soil moisture is within the realm of thinkable situations, although its probability will be small. Some of the flood management activities will no longer be effective for a flood of that magnitude. Instead, there is a need for an increased focus on reducing the vulnerability of the system (Prudhomme et al., 2010; van Pelt and Swart, 2011; Blöschl et al., 2013b). Such measures may not be optimum in an economic sense but may be more robust than alternative approaches if a flood goes beyond the limits of past experience. For example, the vulnerability can be reduced by designing spillways for levees and by allowing for redundancy in warning systems and emergency plans. It is not unusual for the power system to fail during extreme floods, so redundancy is indeed important.

Land use planning and resettling activities to reduce the value of assets in flood prone area will also contribute to reducing the vulnerability. Participative processes are needed for such activities to find acceptability in a socio-economic context (Carr et al., 2012). From a long-term perspective, the interplay of socio-economic processes with hydrological processes is complex (Sivapalan et al., 2012; Di Baldassarre et al., 2013). In reducing vulnerability one may therefore start with the policy options at the local scale and explore a wide range of possibilities causing extreme floods, including combinations of unfavourable factors, and options for managing them. The flood risk management study of Wardekker et al. (2010) is an example that explores imaginable surprises, something they term "wildcards", to develop a strategy of strengthening the resilience of the city of Rotterdam. A resilience approach may make the system less prone to disturbances and enable quick responses to make it capable of dealing with extremes. For such extremes, as with all floods, the hallmark of integrated flood risk management is the interplay of all measures in a seamless way. Comparative flood analysis studies as presented in this paper are an essential basis for developing more efficient strategies for integrated flood risk management.

Appendix A

Catchment characteristics

Table A1. Catchment area and mean elevation of the catchments used in this paper (Fig. 1).

Stream gauge	Stream	Catchment area (km^2)	Mean elevation (m a.s.l.)
Achleiten	Danube	76 650	829
Donauwörth	Danube	15 100	640
Greimpersdorf	Ybbs	1100	676
Hofkirchen	Danube	45 610	622
Kienstock	Danube	96 000	817
Korneuburg	Danube	101 500	803
Landshut	Isar	7900	702
Obergäu	Lammer	395	1195
Oberndorf	Salzach	6120	1338
Rosenheim	Mangfall	1090	790
Schärding	Inn	25 665	1257
Schwabelweis	Danube	35 450	614
St. Johann	Kitzbüheler Ache	330	1312
Staudach	Tiroler Achen	944	1148
Steyr	Enns	5915	1138
Wasserburg	Inn	11 980	1674
Weißbach am Lofer	Saalach	567	1346
Wels	Traun	3425	819
Wildungsmauer	Danube	104 000	784
Wilhering	Danube	76 450	820

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