International Commission for the Hydrology of the Rhine basin (CHR)

CHR Annual Report 2016

Edited by: Eric Sprokkereef – Rijkswaterstaat, VWM, Lelystad

Photo front page: Flood in June 2016 at the gauging station Lustenau / Alpine Rhine (Höchster Brücke). Photo: Ralf Grabher

Contributors:
Federal Office for the Environment, Hydrology Division, Bern
MeteoSwiss, Zurich
WSL – Institute for Snow and Avalanche Research, Birmensdorf and Davos
Department of Geography at Fribourg University
Laboratory of Hydraulics, Hydrology and Glaciology VAW at ETH Zurich
Federal Institute of Hydrology, Koblenz
German Meteorological Office, Offenbach
Office of the Federal State of Vorarlberg, Bregenz
Central Office for Meteorology and Geodynamics, Vienna
Rijkswaterstaat, Infrastructure and Water Management, Lelystad
Royal Netherlands Meteorological Institute, De Bilt

Secretariat CHR
PO Box 2232
3500 GE Utrecht
Netherlands
Email: info@chr-khr.org
Website: www.chr-khr.org

International Commission for the Hydrology of the Rhine Basin

The International Commission for the Hydrology of the Rhine Basin (CHR) works within the framework of the International Hydrological Programme (IHP) of UNESCO and the Hydrology and Water Resources Programme (HWRP) of the World Meteorological Organisation (WMO). It is a permanent, independent, international commission with the status of a foundation, which is registered in the Netherlands. The following scientific and operational hydrological institutions of the Rhine basin are members of the commission:

- Federal Ministry of Agriculture, Forestry, Environment and Water Management, Division IV/4 - Hydrography, Vienna, Austria,
- Office of the Federal State of Vorarlberg, Division VIIb - Water Management, Bregenz, Austria,
- Federal Office for the Environment, Bern, Switzerland,
- IRSTEA, Antony, France,
- IFSTTAR, Nantes, France
- Federal Institute of Hydrology, Koblenz, Germany,
- Hessian Agency for Nature Conservation, Environment and Geology, Wiesbaden, Germany,
- IHP/HWRP secretariat, Federal Institute of Hydrology, Koblenz, Germany
- Administration de la Gestion de l’Eau, Luxemburg,
- Deltares, Delft, Netherlands,
- Rijkswaterstaat - Traffic and Water Management, Lelystad, Netherlands

1. Hydrologic overview for the Rhine drainage basin

Meteorological characteristics

Austria, source: Central Institution for Meteorology and Geodynamics (Zentralanstalt für Meteorologie und Geodynamik, ZAMG)
The year 2016 was the fourth warmest year in Austria since the beginning of instrumental recording in 1768, with a deviation of + 1.0°C from the temperature average between 1981 and 2010 (Figure 1). The three warmest years in the record history were all in the recent past: 2014, 2015 and 1994. The year 2016 had ten warm months above average and only two months that were too cold.

Precipitation was 10 percent above the long-term average. This makes it one of the 25 wettest years since the beginning of precipitation recording in 1858. The months with the most precipitation were January with 44 percent more precipitation than average, February with plus 105 percent, May with plus 47 percent and June with plus 37 percent compared to the average of the last years.

Despite the many wet months, the sunshine duration in 2016 was four percent higher than during an average year. This corresponds to a plus of around 60 hours of sunshine. The sunny months of August, September, November and December contributed particularly to this result slightly above average.

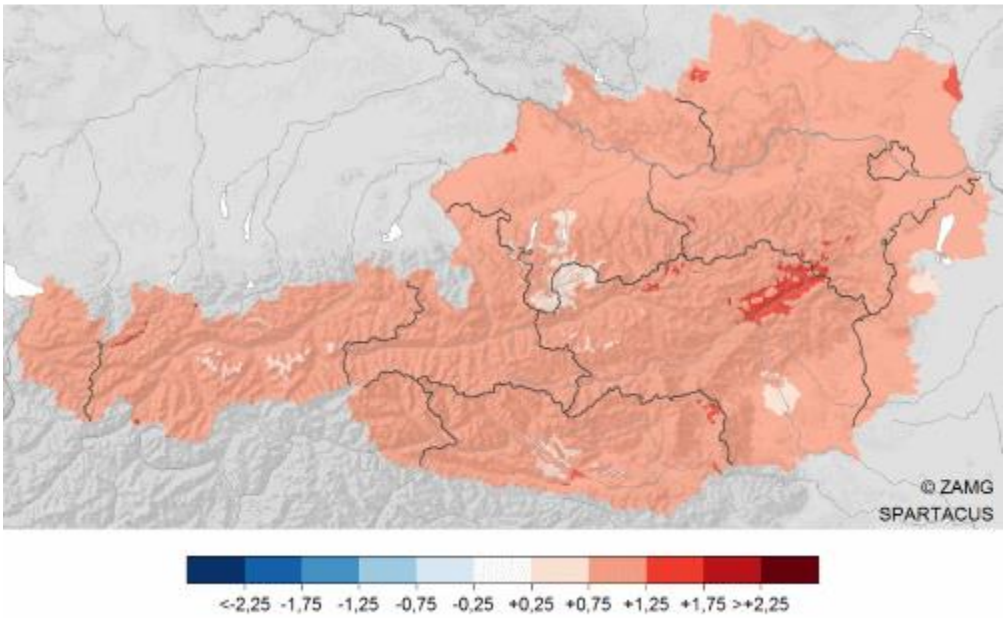


Figure 1: Temperature in Austria in 2016: Temperature deviation from the long-term average 1981-2010. Source ZAMG

Meteorological characteristics for the Austrian Rhine basin
The precipitation rate in the Austrian part of the Rhine catchment area was between 100 and 120 % of the combined average of the last years. In January, February, April to June and August, the total precipitation was above average for the respective months; November was average. Otherwise, monthly precipitation was below average. The air temperature was 0.5 to 1.0°C above the combined average of the last years in the Austrian Rhine catchment area.

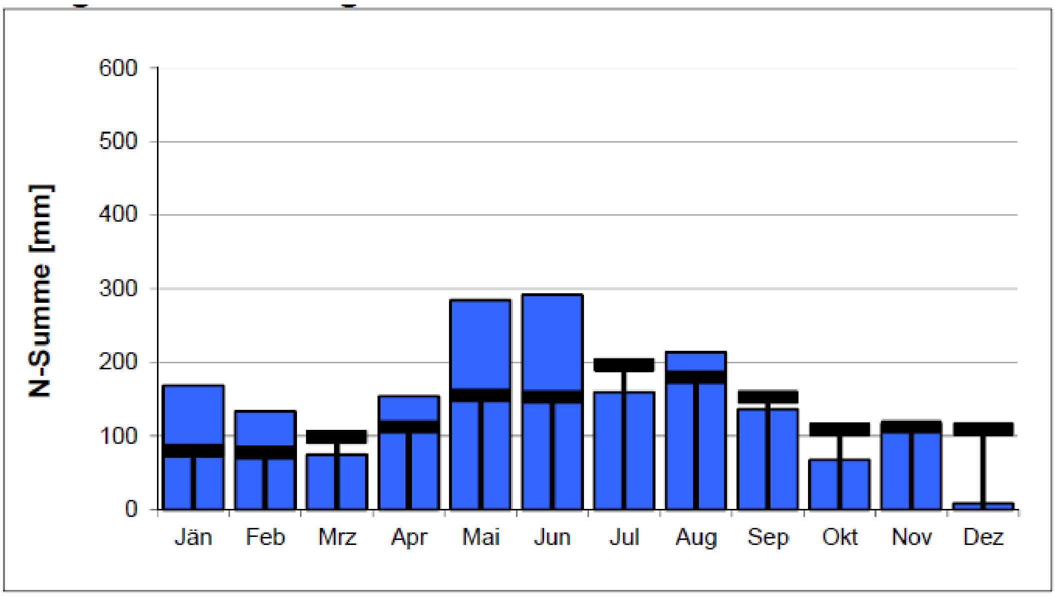


Figure 2: Monthly precipitation totals in 2016 (blue bars) in comparison with the long-term monthly average at the Bregenz Altreuteweg measuring station

Switzerland, Source: Federal Office for Meteorology and Climatology (MeteoSwiss)
At the northern side of the Alps, precipitation in January was particularly high. The frequent and, towards the end of the month, heavy precipitation led to record measurements for January even in measuring stations with records dating back more than 100 years. At lower elevations at the northern side of the Alps, it was the second wettest January since beginning of the recording in 1864. Alternatively, the southern side of the Alps experienced only half the normal January precipitation. February was very mild in general with several very warm periods. During the first days in March, southern Switzerland experienced heavy snowfall with daily totals that have only rarely been observed.

In general, precipitation was high in many areas in spring. Except for the southern side of the Alps, precipitation was low only in March. Precipitation was above average in April and especially in May.

June was mainly foggy and rainy. Thunderstorms brought heavy rainfall during the first half of the month. Wet air mass from Mediterranean areas brought torrential rainfalls in southern and eastern Switzerland. The torrential rainfalls and wet grounds due to the previous wet weather in June resulted in landslides and flooding. During the last third of the month, heavy thunderstorms again caused damage in the east of the country. The first half of the year concluded with the highest total precipitation rates on the northern side of the Alps since beginning of the recording. Except for March, precipitation was above average during all months until the middle of the year.

There were approximately 20 summer days at the northern side of the Alps in July and August. At the southern side of the Alps, it was almost continuously warm in July and August with 26 to 28 summer days. From 22nd August onwards, a high-pressure area moved across central Europe, which dominated the weather up until 28th August. Due to persisting high-pressure dominated weather, regions on the southern side of the Alps, in Valais and west Switzerland experienced the warmest September since beginning of the recording.

October was too cold and brought an end to the unusually warm late summer. Snowfall in areas of medium elevation and several days with ground frost in low-lying regions brought an early winter in October. The first half of November brought wintery cold weather. There was a large amount of snowfall in the mountains during mid-November.

Due to persisting high-pressure weather, the northern side of the Alps and regions in the Alps experienced a December with the lowest amount of precipitation since beginning of the recording in 1864. There was no precipitation in December in some regions in the centre of the country and in Valais. Due to the persisting dry and mild weather in the mountains, the Alps were free from snow up to an altitude of just under 2000 m. At an altitude of 2500 m, the snow was only 20 to 30 cm deep.

Table 1: Annual values for 2016 at selected MeteoSwiss measuring stations compared to the 1981-2010 standard

Station	Altitude	Temperature (°C)			Sunshine duration (h)			Precipitation (mm)		
	a.s.l.	Average	Standard	Dev.	Total	Normative	%	Total	Normative	%
Berne	553	9.4	8.8	0.6	1760	1683	105	1056	1059	100
Zurich	556	9.9	9.3	0.6	1642	1544	106	1297	1134	114
Geneva	420	11.1	10.5	0.6	1821	1768	103	886	1005	88
Basel	316	10.9	10.5	0.4	1640	1590	103	997	842	118
Engelberg	1036	7.3	6.4	0.9	1357	1350	101	1612	1559	103
Sion	482	11.2	10.1	1.1	2086	2093	100	587	603	97
Lugano	273	13.3	12.4	0.9	2138	2069	103	1681	1559	108
Samedan	1709	2.8	2.0	0.8	1773	1733	102	750	713	105

Standard = Long-term average 1981-2010
Dev. = Deviation of the temperature from the standard
% = Percent in relation to standard (standard = 100%)

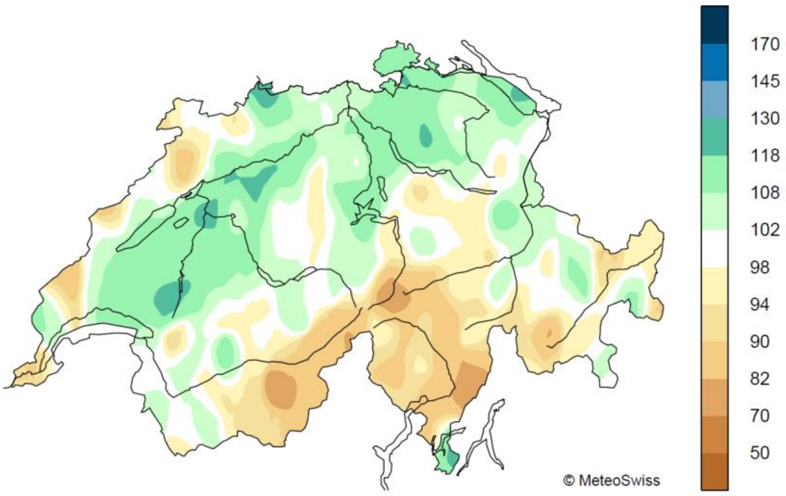


Figure 3: Annual precipitation totals for Switzerland in 2016 in percent of the standard (1981-2010).

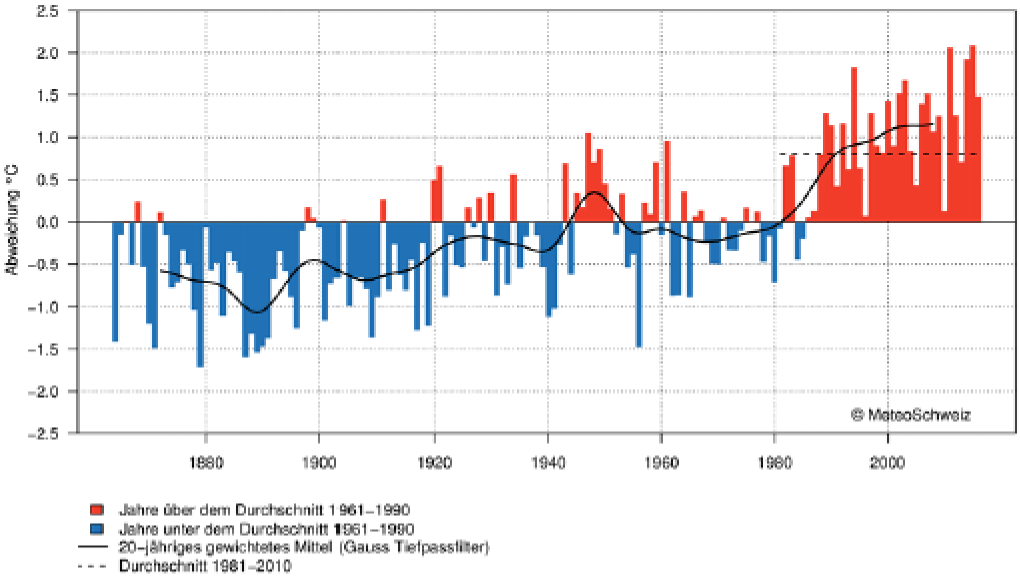
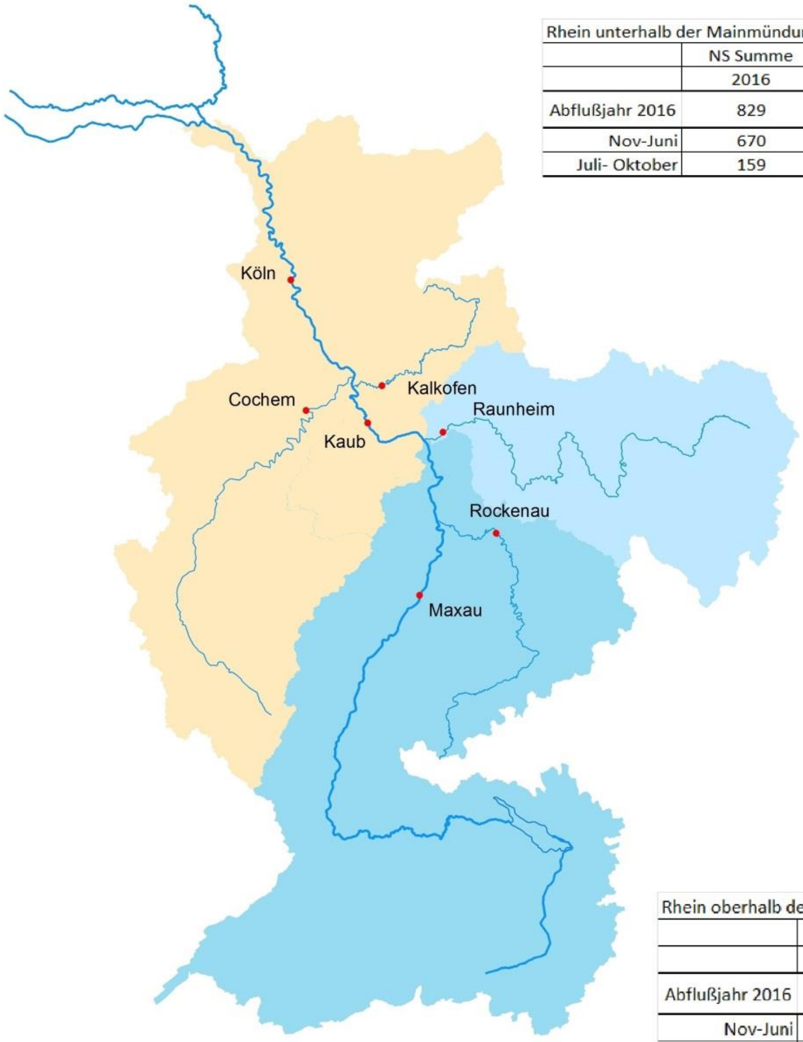


Figure 4: Annual temperature deviation from the long-term average (reference period 1961-1990) in Switzerland in 2016. The too-warm years shown in red, the too-cold years are shown in blue. The black solid line shows the temperature profile averaged over 20 years.

Germany, Source: German Weather Service (Deutscher Wetterdienst, DWD)
Global temperature records non-stop - the average temperature of the calendar year 2016 exceeded the previous record holder 2015. In Germany, the year 2016 was on position eight together with another six years. Similar to the previous year, 2016 was too warm and too dry in almost all of Germany (source: DWD / Annual Short Report 2016).

The relative deviations of precipitation totals in the country during the discharge year (Nov. 2015-Oct. 2016) show a "wet trend" for the first eight months of the observation period. For the Rhine, this means that the precipitation totals during the last third of the discharge year were on average 23% below the values of the reference period 1981-2010, which is considerable. In relative terms, the driest area was the catchment area below the Main estuary; precipitation totals of only 159 mm were measured, which is only slightly higher than half the average to be expected during the period from July to October. (see Figure 5 with tables).



Rhein unterhalb der Mainmündung				
	NS Summe	%	NS Summe	%
	2016		1981-2010	
Abflußjahr 2016	829	91	908	
Nov-Juni	670	81	606	67
Juli- Oktober	159	19	302	33

Main				
	NS Summe	%	NS Summe	%
	2016		1981-2010	
Abflußjahr 2016	780	98	800	
Nov-Juni	596	76	523	65
Juli- Oktober	184	24	277	35

Rhein oberhalb der Mainmündung				
	NS Summe	%	NS Summe	%
	2016		1981-2010	
Abflußjahr 2016	1019	103	993	
Nov-Juni	790	78	651	66
Juli- Oktober	229	22	342	34

Figure 5: Rhine basin: Comparison of the precipitation totals and discharge averages in the discharge year 2016 with the long-term average 1981/2010 (Source: DWD / monthly weather reports 2016)

For the upper Rhine basin, the seasonal precipitation statistics show an almost even distribution of precipitation totals of 51% and 49% for the winter months and the summer months. For the Main basin (54 and 46%) and the basin below the Main estuary (55 and 45%), precipitation totals increased with respect to the long-term averages during the winter months. Overall for the winter months, precipitation totals of 470 mm (109%) were recorded for the winter months, while the summer months showed a considerably lower precipitation of 405 mm (86%) in relation to the long-term precipitation averages for the same period (471 mm). However, the calculated average precipitation of 97% for the Rhine basin during the observation period is almost as high as the average.

When considering the monthly precipitation totals in comparison to the long-term monthly averages, the months December and July to October experienced a considerable deficit between 47 and 76%. The minimum with only 33 mm was measured in September. Precipitation totals clearly exceeded the long-term average in the months November, February and June with 142-158%. The maximum with respect to monthly totals of 132 mm was measured in June (see Figure 6.a).

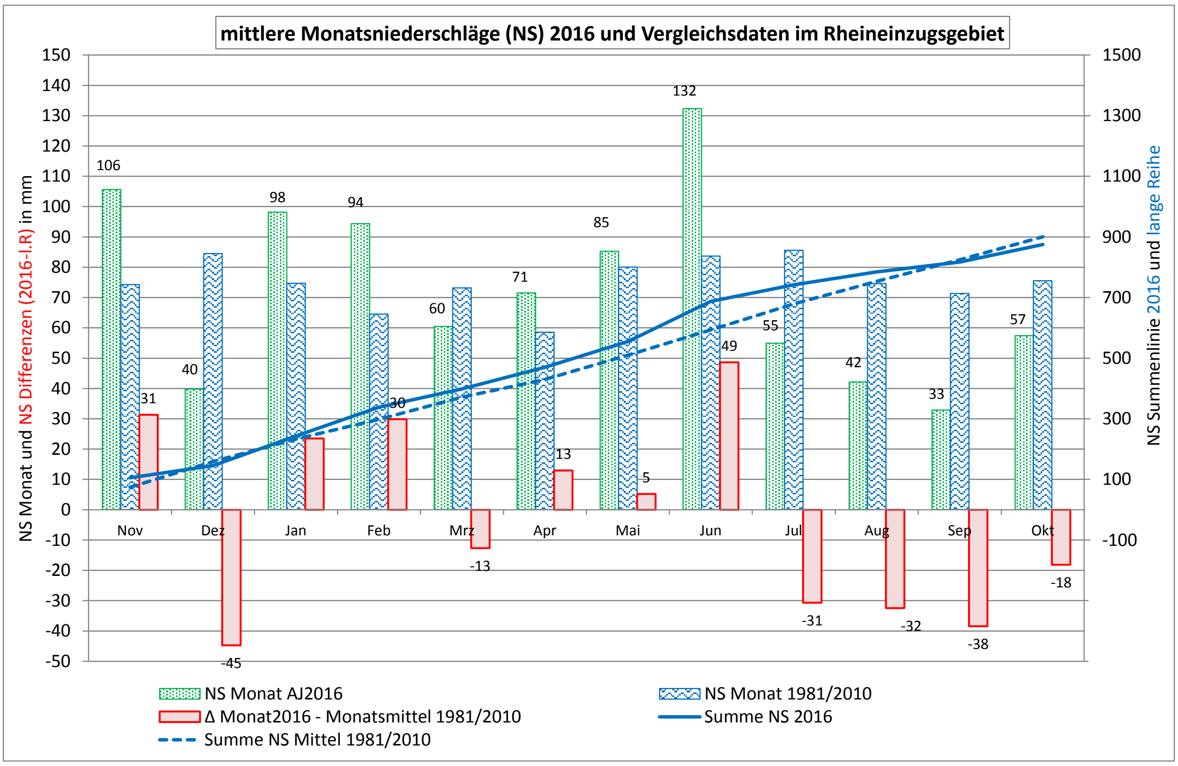


Figure 6a: Rhine basin: Comparison of the monthly precipitation totals in the discharge year 2016 with the long-term average 1981/2010 (Source: DWD / monthly weather reports 2016)

With respect to the annual average temperature of 10.2°C, the discharge year 2016 can be classed as a very warm year. With an annual average of 11.6°C at the measuring station Cologne, the annual average deviated by +1.3 K with respect to the reference period 1981/2010, where a deviation of +1.7 K was measured particularly during the mild winter months. During the months November and December 2015 (+3.3 and +5.6 K) as well as September 2016 (+3.5 K), the highest monthly average temperatures since the beginning of systematic measurements in 1881 were recorded. Temperatures were slightly below average only in the months March, April and October (see Figure 6.b).

The water temperatures measured at the gauge in Cologne deviated from the average values in a similar fashion to the temperature measurements during the first third of the discharge year. From November 2015 to February 2016, the average was 1.4 K above the long-term average. However, temperatures were below the monthly averages by 0.2 to 0.3 K for the remainder of the year. The average water temperature in September was considerably higher than the monthly average of 21.6°C with a deviation of +2.3 K (Figure 6.b).

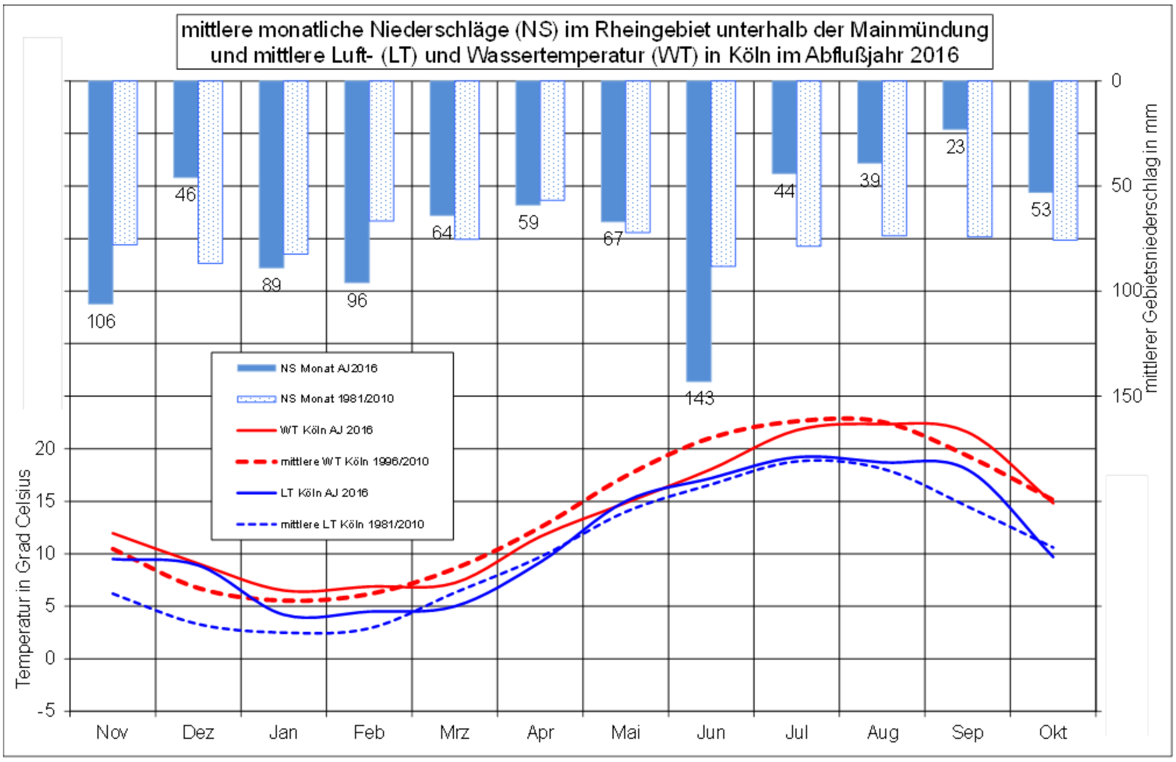


Figure 6.b: Rhine basin/example station Cologne. Comparison of the monthly temperature and precipitation data in the discharge year 2016 with the long-term average (Data sources: LT and NS - DWD, WT - WSV)

Netherlands, Source: Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut, KNMI)

The average annual temperature at the De Bilt station reached a value of 10.7°C in 2016, compared to a normal temperature of 10.1°C. Thus, 2016 was the tenth warmest year since 1901.

The months January and February were both fairly mild. Spring began late. March and April were characterised by periods with northern currents and mainly cold weather. In contrast, May was predominately warm. The summer was very warm and was the tenth warmest summer since 1901. There was more sunshine than normal, but summer was also wetter than normal. Especially the nights were warm. On 20 July, the highest temperature of the year with 35.2°C was measured in Eindhoven. The end of August was warm and this continued into September. It was the second warmest September since records began with a monthly average of 17.3°C in De Bilt. The months October and November were colder than normal and December was unusually mild (see Figure 7).

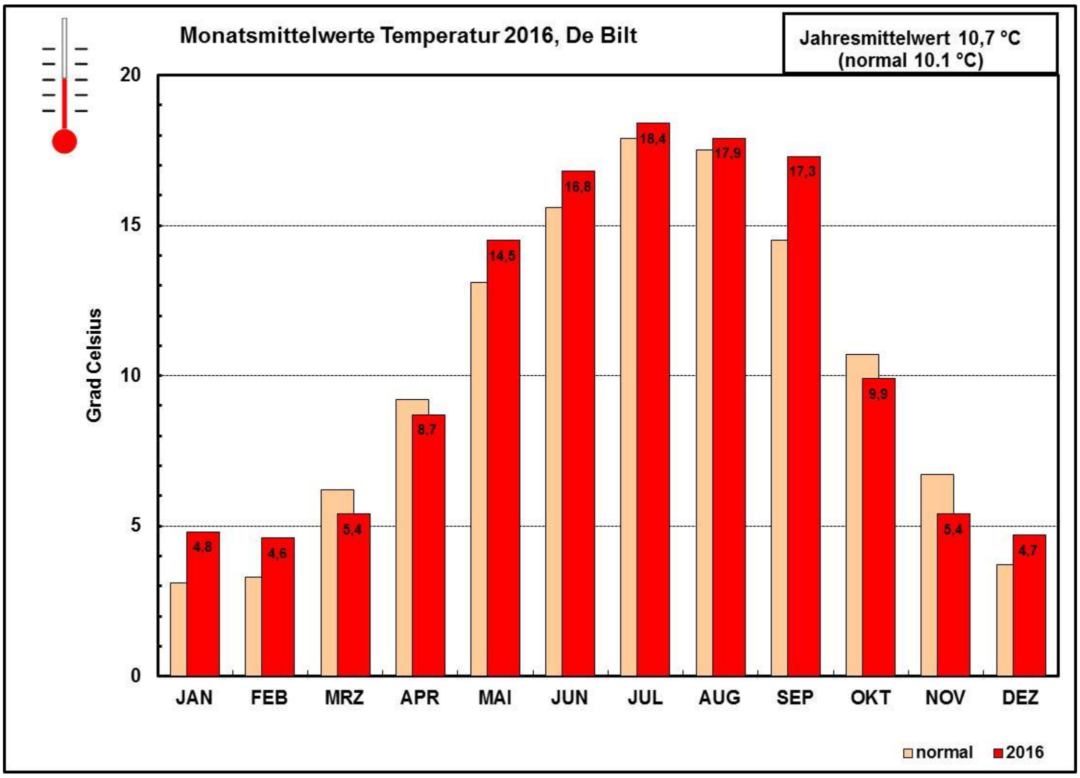


Figure 7: Monthly average temperatures at the De Bilt station in 2016 compared to long-term (1981-2010) averages (Source: KNMI)

On average, 1881 hours of sunshine were recorded in the last year. This makes 2016 a very sunny year. Sunshine duration of 1643 hours is normal (in comparison to the long-term average 1981-2010).

The average precipitation at the De Bilt station in the last year was 828 mm. The long-term average is 833 mm. However, there were large regional differences. With a deficit of 150 mm, the weather in the north was too dry, while the weather in the southern and western part of the country was too wet.

June was extremely wet with a monthly total precipitation of 277 mm measured in the southeast of the country (Limburg). There were repeatedly heavy thunderstorms in the south and east of the country, which moved only very slowly leading to high amounts of precipitation locally. In the evening of 23 June, hail stones with a diameter of up to 10 cm caused in areas of the southeast great damage. January and February were wet months, and September and December were too dry. There was hardly any snow. A few centimetres of snow fell in the northeast during the cold periods between the 3rd and 7th of January and the 16th and 22nd of January.

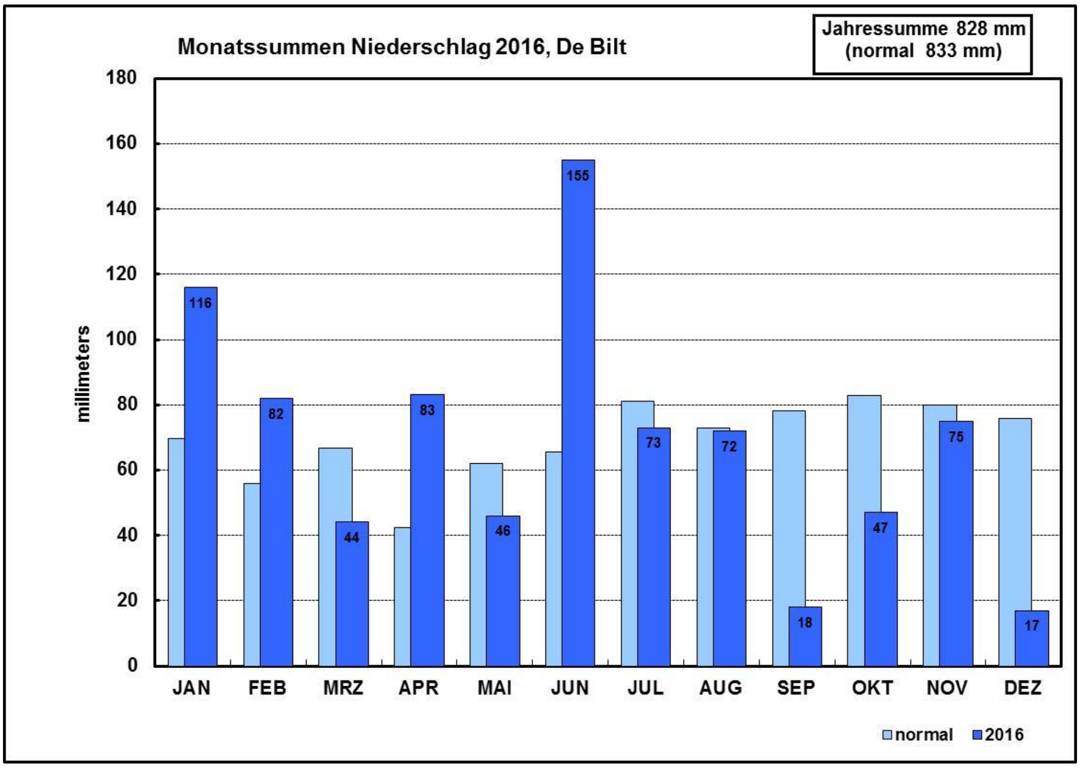


Figure 8: Monthly precipitation totals at the De Bilt station in 2016 compared to long-term (1981-2010) averages (Source: KNMI)

Snow and glaciers

Reference: Snow: WSL-Institute for Snow and Avalanche Research SLF
Glaciers: Geographic Institute of the University of Fribourg and Laboratory for Hydraulics, Hydrology and Glaciology (VAW)

In October 2015, the snow line dropped repeatedly to medium altitudes. The most precipitation fell in the area of the central Alpine divide, in south and east Switzerland. Snow remained particularly on high mountains and formed a thin, closed cover especially on the glaciers.

The first three weeks of November were sunny and extremely mild. Two wintery episodes in the fourth week of November marked the start of the winter season at least in the north and west. The weather remained dry in the south and east. During the entire month, snow depths in the north and west were slightly below average. Areas of medium altitude in the south and Graubünden were free from snow.

There was no snow in December. The small amounts of snow during early winter were even more pronounced than in the previous winter 2014/15. Where a thin layer of snow formed, it melted again in many areas. Areas at altitudes of 2000 m a.s.l. were free from snow at the end of the year, which has never been observed at the long-term measuring stations at the southern side of the Alps.

There was heavy snowfall repeatedly in the west and north and temperatures fluctuated. The snow situation was average only in the west, but otherwise below average in large areas and considerably below average in the south.

After a spring like start of the month, February saw a lot of snow and was wintery. As observed in January, there was heavy snowfall in the west and north but also in the south. After those heavy snowfalls in February, the snow situation above an altitude of around 1400 m was only slightly below average at the end of the month in central and east Switzerland and above average in western Switzerland.

March was relatively cold and started with an atypically heavy onset of winter weather in the south. After a calm second week in March, around 50 cm of snow fell even in lower-lying areas in the middle of the month.

Between the end of March and mid-April, there was a lot of snowfall in several episodes above 2200 to 2400 m. In areas of medium and low altitude, the snow cover melted in the rain. It also melted in the north due to the mild weather and disappeared in some regions during the first week in April. But winter was not over yet, it came back in the middle of April: Up to 50 to 80 cm of snow fell above an altitude of 2200 m in Graubünden and up to 100 cm in the area of the central Alpine divide and in Upper Engadine. Despite the late wintery weather, the snow situation in April was generally below average. Average snow depths were only measured in Lower Valais.

The winter of 2015/2016 was good for the Swiss glaciers. Above average snowfall was recorded in the west in April and May, while the amount of snow was average in the east and south. Snow melting was delayed due to a rather foggy June and new snow fell repeatedly on the glaciers. Thus, they were relatively well covered in snow at the start of the first heat wave of the summer. The stable summery weather in August and the warm first half of September were problematic for the glaciers.

The glacial mass was determined for 20 Swiss glaciers in September 2016. The ratio of growth due to snow to loss due to melting was again negative this year. For the summer of 2016, large regional differences became apparent again at the time of the analysis: The glaciers in the west and in the Bernese Oberland showed only relatively small ice thickness losses of around 30 cm (Glacier de Tsanfleuron, Glacier de la Plaine Morte). Both glaciers lost the greatest amount of mass by a long way in 2015. On the other hand, south Valais and Engadine experience substantial losses. The glacier Griesgletscher suffered the most with an average thickness change of almost two metres. The mass of glaciers in central and east Switzerland was about the same as the average of the last ten years - that means that the melting of the glaciers continues.

Applied to all glaciers in Switzerland, this means an estimated loss of volume of around 900 million cubic metres of ice for the hydrological year 2015-2016. The amount of water equals roughly the annual drinking water consumption in Switzerland. Thus, the currently present glacier volume was reduced by over 1.5% this year. The melting of the glaciers was average in comparison with the last decade. The glaciers experienced greater losses in the extreme years of 2003, 2006, 2011 and 2015.

Hydrological situation in the Rhine basin in the year 2016

Water levels of the large lakes in the Rhine basin

Austria

The above average precipitation totals during the first half of the year resulted in the highest water level of Lake Constance since 1999. On the 20th and 21st of June, the water level at the gauge in Bregenz was 516 cm, which is just above the 10-year flood level. Precipitation totals were below average in the second half of the year. From September onwards, every day the water level was below the average level for the respective calendar day of the reference period 1864-2013 except for a period from 19 November to 9 December (see Figure 9).

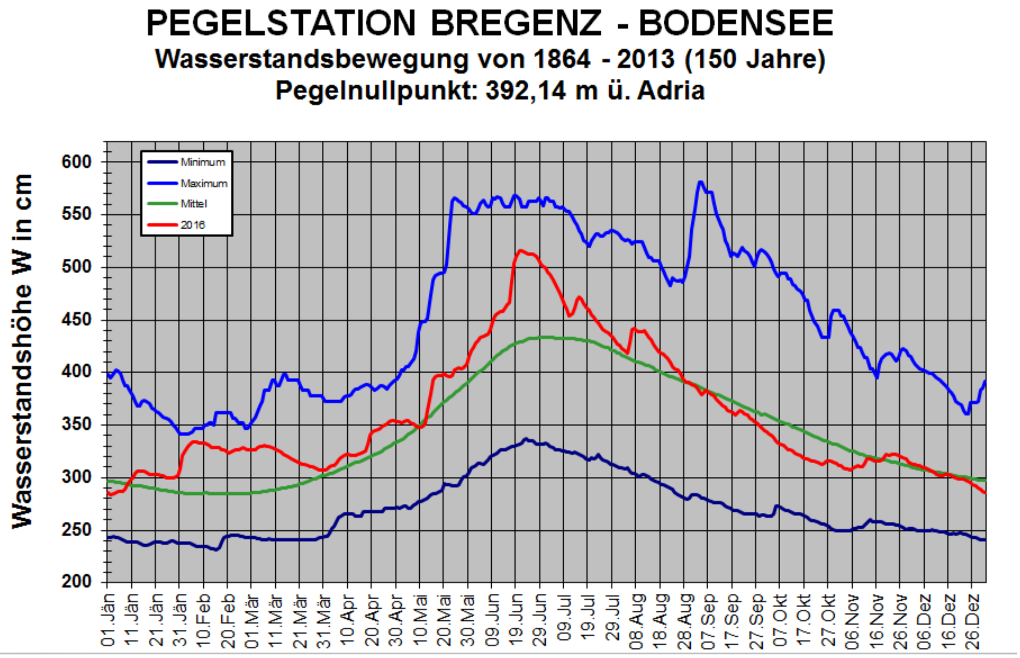


Figure 9: Hydrograph of the water level in Lake Constance at the Bregenz gauge in 2016 (red curve) compared to long-term lows, highs and average values of the period 1864-2013.

Switzerland

There were considerable deviations of the annual average water levels from the long-term averages at Lake Constance and Lago Maggiore. The water level in Romanshorn at Lake Obersee was 26 cm above and the water level in Locarno at Lago Maggiore was 27 cm below the average from 1981 to 2010. The water levels of Lake Thun (-6 cm) and Lake Brienz (-5 cm) were also below the long-term averages by a few centimetres. The lowering of the water level at Lake Thun was instrumental here: During a so-called extraordinary lowering of the water level, a lower level is maintained from 20 January to 20 February if the weather permits. This makes it possible to conduct construction works at the lake front. Water levels are lowered every four years at both lakes but never at the same time. The annual water level averages of the other larger lakes were below or above the long-term average by only a few centimetres.

At Lake Constance, all monthly averages of 2016 were greater than the respective long-term averages. There were particularly large differences immediately after the floods in mid-June. The water level was considerably above normal values during the summer months in June (+71 cm), July (+52 cm) and August (+40 cm). A continuous deviation of the water levels from normal values was observed at Lake Constance in the last years. This is another reason

why all monthly averages were above normal this year. The behaviour of Lake Neuchâtel was much more balanced in 2016. The greatest deviations from normal were 12 cm (+12 cm in June, -12 cm in December). The monthly averages of Lago Maggiore showed even greater deviation from normal than Lake Constance. At the beginning of the year, the water level was below the long-term average for January by more than one metre. Subsequently, the negative differences decreased continuously. The monthly averages from April to July were above normal. The dry autumn caused the water level to go down again, and the differences were about the same as at the beginning of the year in September (-82 cm) and October (-93 cm). Towards the end of the year, the large deficits were reduced and the water level of the lake rose considerably. At Lake Geneva, water levels were below average in March (-15 cm) and above average in June (+15 cm). However, deviations from normal were only small at the beginning of the year and in the second half of the year.
The heavy and persistent precipitation from mid-June onwards in the central eastern regions of the foothills of the Alps caused an increase of the water level at Lake Constance, which has not been recorded since 1999. In June and July, the water level was higher than the flood levels relevant for warning for more than 40 consecutive days. The threshold for the second highest warning level (great risk, 397.15 m a.s.l.) was exceeded for two weeks. The highest level of 2016 was reached on 21st June (397.35 m a.s.l.) but remained below the highest level of 1999 by more than half a metre.

Water levels were extremely low in some lakes in 2016. The lowest water level of Lake Neuchâtel was reached at the end of the year. On 31st December, the level was 24 cm below the long-term monthly average and only 6 cm above the lowest level of the entire record period since 1983. There were two low-level phases at Lago Maggiore: one at the beginning of the year and the other in autumn. The water levels of Lake Geneva were around in the lower normal range and then increased quickly to above average levels. Despite this, the highest water level of 2016 was around 30 cm below the June maximum of 1970.

Water levels and discharges of river water

Austria
The discharge of the Alpenrhein in 2016 was the same as the long-term average. The discharge of the most important tributaries to Lake Constance from Austria was above average. The annual load compared to the long-term average was:

- 111% for the Bregenzerach (MQ 2016 = 51.5 m^3/s, longer-term MQ = 46.4 m^3/s);
- 115 % for the Dornbirnerach (MQ 2016 = 8.07 m^3/s, longer-term MQ = 7.02 m^3/s);
- 100 % for the Alpenrhein (MQ 2016 = 231 m^3/s, longer-term MQ = 231 m^3/s);

The flood at the Alpenrhein on 17 June 2016 must be categorised as 10-year event.

Switzerland
In the large river basins at the northern side of the Alps, the annual averages were a few percent above the values of the reference period 1981-2010. The discharge of the Alpenrhein was pretty much exactly the same as normal. The annual averages of the river basins at the southern side of the Alps, in Engadine and Valais were below. Ticino reached 81%, Maggia 85%, Inn 90% and Rhone 95% of the long-term averages.

The apparent balance of the annual discharge resulted mainly from a wet first half and dry second half of the year in many regions. This is particularly apparent in some medium-sized drainage basins. The monthly discharge of the Doubs was twice as high in February and June than in the respective months of the reference period. They were only one third in September and only one fifth in October and December of the long-term monthly averages. A similar observation was also made in 2015: with a flood situation at the beginning of May, an unusually dry and hot summer and autumn with little precipitation. In the larger drainage basins, this behaviour is less pronounced than in the medium-sized basins but it was also observed at the Reuss and the Limmat. Considering the monthly discharges of the first half of the year, June is especially noticeable. The June discharges in the larger and medium-sized drainage basins in 2016 were greater than the June discharges of the reference period. The Massa near Blatten is an exception with a largely glacier-dominated drainage basin. The snow started to melt later due to the foggy weather. New snow continued to fall on the glaciers protecting them from the first heat wave of the summer. During the second half of the year, the months October and December are particularly noticeable with largely low discharge rates. Precipitation totals in December were the lowest since records began in 1864 so that the discharges in some basins were reduced to around one fifth of the normal discharge volume. These drainage basins are the Emme, Thur, Doubs and Venoge.

The profile of the daily averages illustrates how the high monthly discharges were reached in June: The Alpenrhein exhibited a considerable, short event during which the discharge increased rapidly and then decreased rapidly again. A new June maximum was recorded at the gauging station in Diepoldsau. It was around 500 m^3/s below the absolute maximum of July 1987 (records since 1984). Aare, Reuss and Limmat behaved differently: There was a relatively major and fast discharging flood event in these three drainage basins already in May. Once the discharges had reduced to a normal level for the time of year, the levels rose considerably again and remained high for a longer period. One reason for the dampening and slower reaction of the discharges in these three basins is the large lakes, which held water back and discharged it with a delay. Where such a dampening effect is not present, heavy precipitation results directly in discharge - especially in smaller drainage basins. Good examples for this are the Emme and Muota.

There were months with new monthly maxima as well as months with new monthly minima, which seems appropriate for this variable year. An accumulation of monthly maxima was recorded in May and especially in June. There was a cluster of monthly minima in January, October and December. Another aspect showing the aggravation of the situation with low water levels at the end of the year is the time at which the lowest water levels were recorded. Out of the included 170 discharge gauging stations for which the time of the lowest water level was analysed in August 2016, a quarter of the stations showed the minimum for the months of August (1%), September (7%), October (15%) or November (3%). For the other three quarters of the stations, the discharges decreased even further in December. For more than 100 stations (60%), the trend continued downwards at the end of the year and the lowest levels were observed in the beginning of 2017.

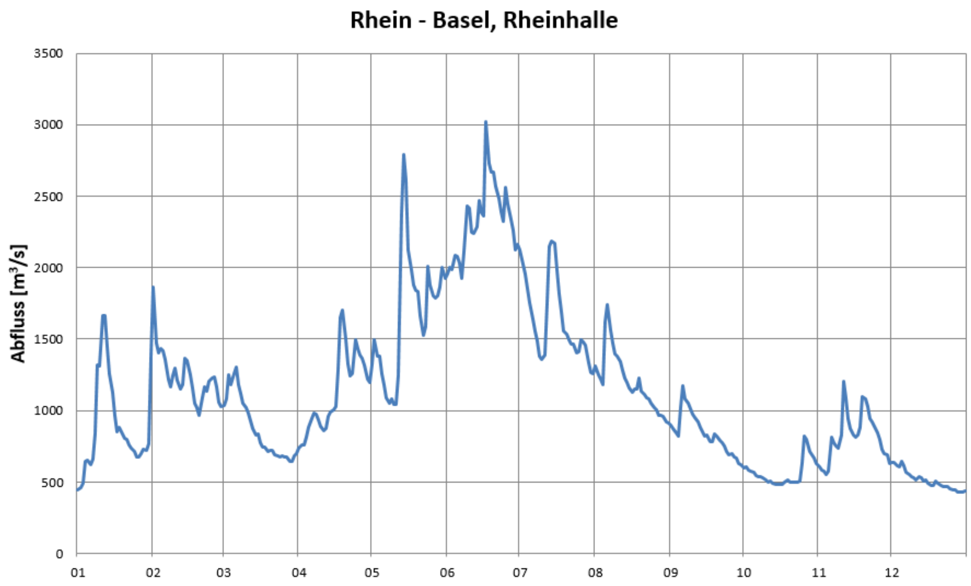


Figure 10: Discharge hydrograph at the Rhine - Basel gauge, Rheinhalle in 2016

Germany

The discharge events of the discharge year 2016 (illustrated in the graphs in Figures 12 to 17) were characterised by the low water level situations at the beginning and the end of the observation period. This was in contrast to late spring flooding, which occurred at the end of May due to an extreme weather situation (see BfG report): Weather with heavy rainfalls and thunderstorms in central Europe had some disastrous consequences. In some areas, flooding events of the category "flash flood" caused great damage (e.g. in Braunsbach, Baden-Württemberg on 29/05). Large-scale flooding in the Rhine basin did not occur in most places. The Neckar was affected the most. Here, the discharge rate at the gauge in Rockenau reached its peak of 1 370 m³/s, which has a statistical return period of 5 years.

Figure 11: Low flow on the Rhine near Bonn at the beginning of the year in front of the Siebengebirge (Picture: E. Nilson, BfG)

The annual development of the discharges at the Rhine gauges was characterised by the decrease of the low water levels of 2015 during the first two months. At all gauging stations, the long-term annual MQ (period 1931/2011) was underrun. From January to the end of June, the monthly averages were partly above average but showed a clearly decreasing tendency at the beginning of July. The MNQ were underrun until the end of the observation period. Considerable low water levels developed (see BfG reports).

The annual average MQ of the discharge at the Rhine gauging stations was above the long-term averages of the period 1931/2011 (see Table 2).

The ratio of winter MQ to summer MQ shows a clear influence of the low mountain tributaries with an increase in the drainage basin. At the Maxau gauge, the average discharge in the winter months of 43% were above the discharge calculated for the summer and was around the same value as the one for the long-term averages (45 to 55%). The winter percentage at the gauging stations Kaub and Cologne was 4% below the long-term values. The ratio was just below the long-term mean value at the canalized rivers Neckar and Main and similar at the Mosel (see Table 2).

Table 2: Comparison of average discharges (MQ) in the discharge year for selected gauges in the Rhine basin and in relation to the long-term reference period (1931/2011), except Rockenau, Raunheim

Gauge	*MQ*			*MQ 2016*		
	2016	*1931-2011*	*MQ 2016 in % of the MQ of the long-term reference period*	*Winter*	*Summer*	*% Wi/Su (long-term reference period)*
Maxau (Rhine)	1354	1253	108%	1152	1556	43/57 (45/55)
*Rockenau (Neckar) * 1951-2011*	131	137	95%	150	111	58/42 (64/36)
*Raunheim (Main) * 1981-2011*	201	225	89%	262	140	65/35 (68/32)
Kaub (Rhine)	1773	1653	107%	1656	1890	47/53 (51/49)
Cochem (Moselle)	369	314	118%	483	256	65/35 (64/36)
Cologne (Rhine)	2285	2110	108%	2316	2254	51/49 (55/45)

The long-term collected annual MQ were underrun at the Rhine gauge Maxau on 175 days; on 66 days during the winter months and on 109 days during the summer months. Values were below average in Kaub on 150 days (75 in winter and 95 in summer) and in Cologne on 174 days (91 and 83). At the Rhine gauges, the discharge was clearly below average from mid-August onwards. The developing low water levels of 2017 were beginning to show. Averages were exceeded during the observation period at the tributaries Neckar and Main on 108 and 116 days, respectively, and at the Moselle on 160 days. The ratio of winter/summer showed a clear tendency towards the winter at Neckar (77/35), Main (94/22) and Moselle (118/42). In contrast to the development of low water levels measured at the Rhine gauging station from the beginning of August onwards, low water levels were observed at the tributaries already at the beginning of July.

In the entire Rhine basin, discharges were below the monthly long-term average discharges (mMQ) during the summer months: in Maxau on 253 days (winter 127, summer 123), in Kaub on 199 days (114/85) and Cologne on 186 days (104/82). At the Neckar and Main, the below average days of 253 days (127/126) and 264 days (134/130), respectively, were considerably above the ones determined for the Moselle with 176 (76/100).

Noticeable below average annual discharge (MNQ) was measured at the Rhine gauges on 28 days. There were none at the Neckar, 9 days at the Main and 44 days at the Moselle (Cochem). During the year, discharges were below the monthly average minima (mMNQ) on average on 77 days; at the tributaries Neckar on 81 days (winter 45, summer 36), Main on 64 days (winter 35, summer 29) and Moselle on 126 days (winter 43, summer 83).

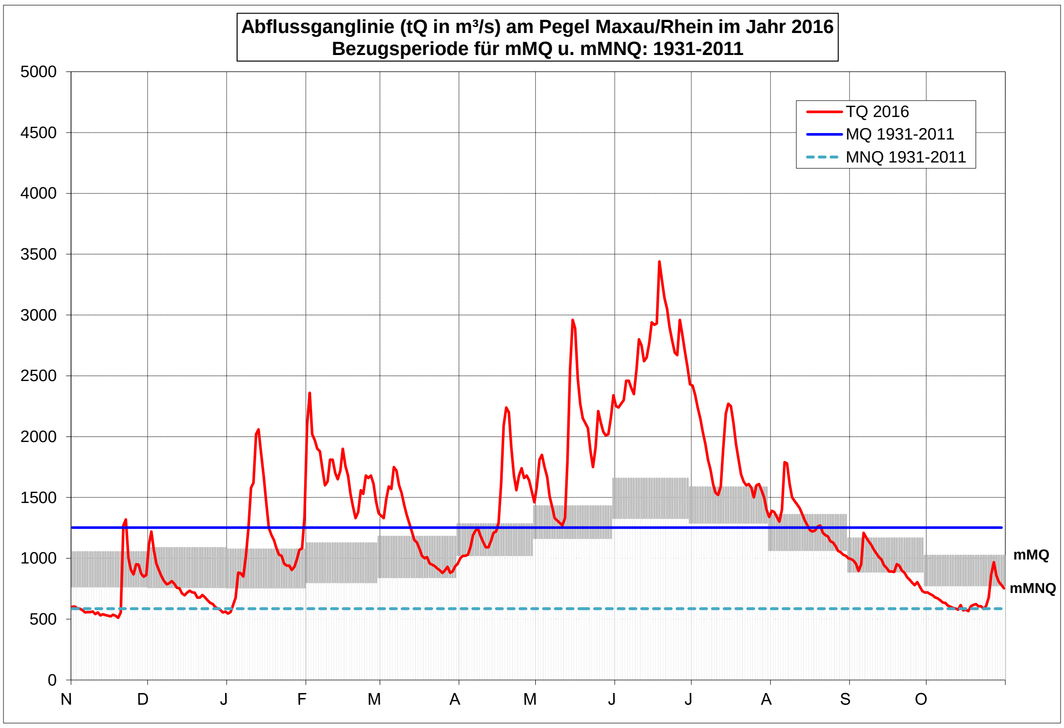


Figure 12: Daily discharge (tQ) at the gauge in Maxau (Rhine) in 2016 in comparison to the long-term averages in m³/s (reference period of MQ, mMQ and mMNQ: period 1931-2011)

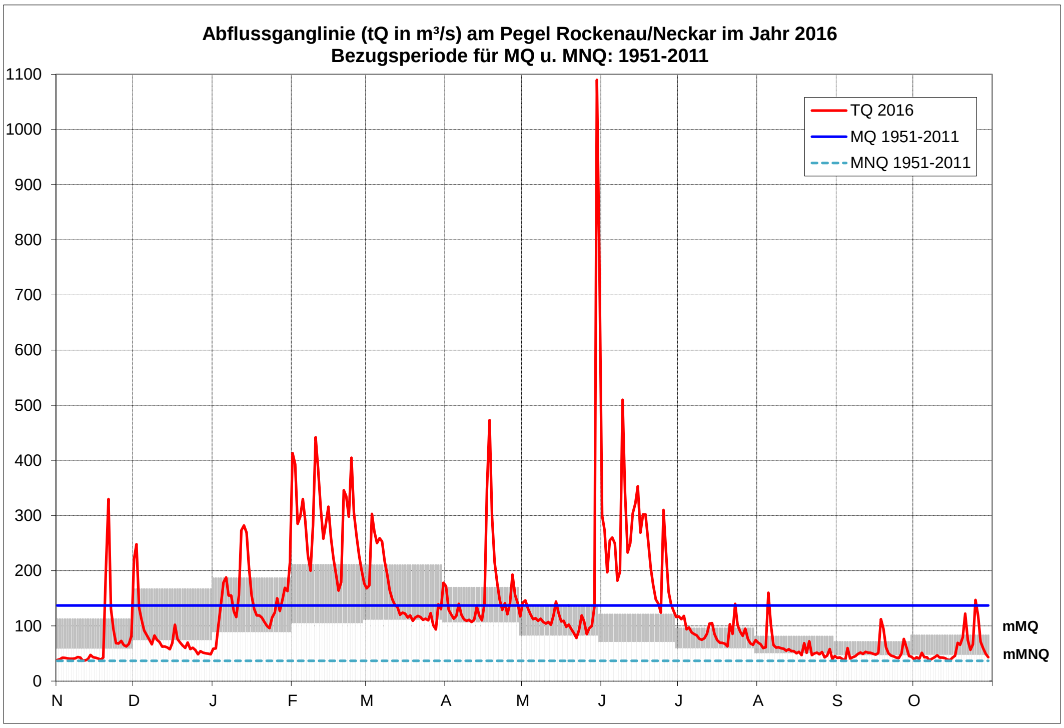


Figure 13: Daily discharge (tQ) at the gauge in Rockenau (Neckar) in 2016 in comparison to the long-term averages in m³/s (reference period of MQ, mMQ and mMNQ: period 1951-2011)

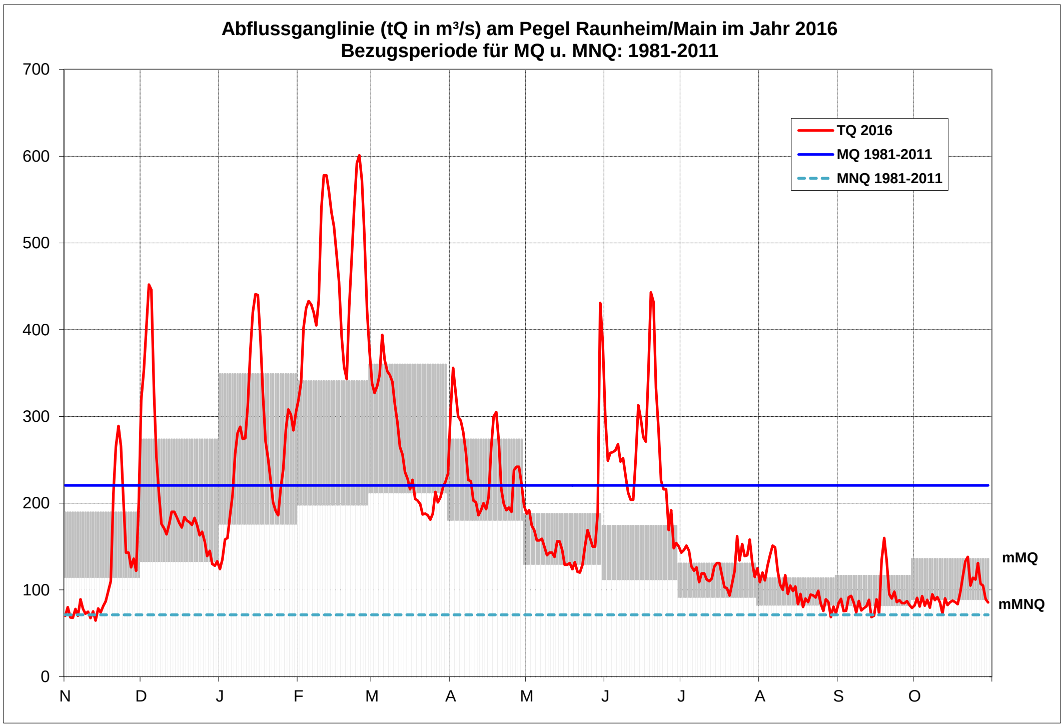


Figure 14: Daily discharge (tQ) at the gauge in Raunheim (Main) in 2016 in comparison to the long-term averages in m³/s (reference period of MQ, mMQ and mMNQ: period 1981-2011)

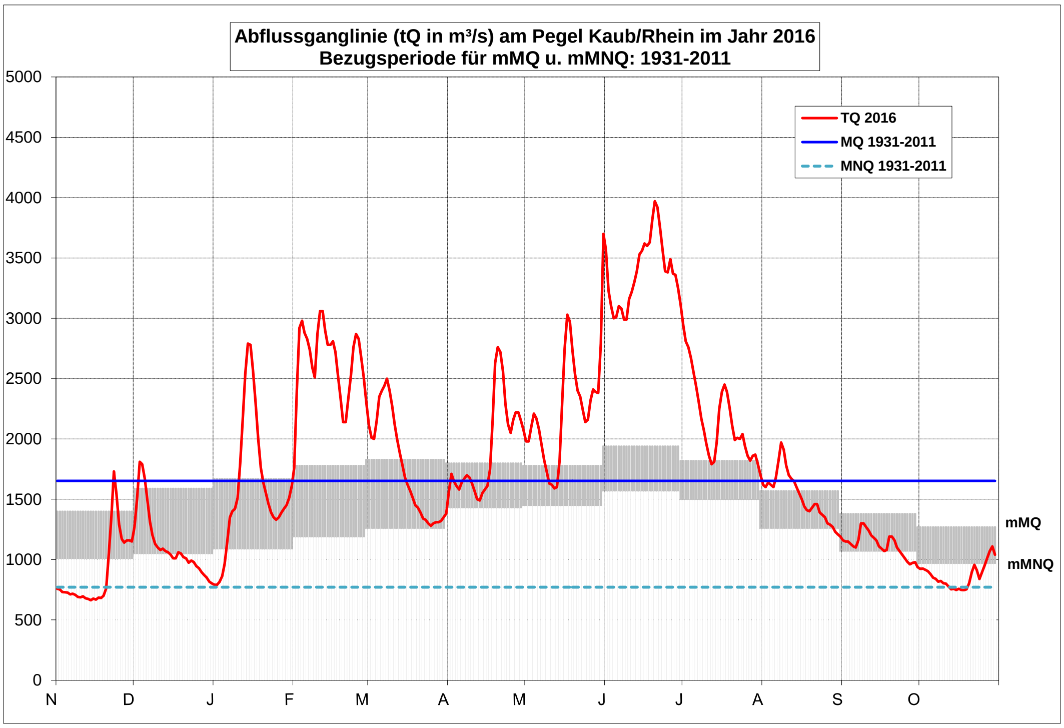


Figure 15: Daily discharge (tQ) at the gauge in Kaub (Rhine) in 2016 in comparison to the long-term averages in m³/s (reference period of MQ, mMQ and mMNQ: period 1931-2011)

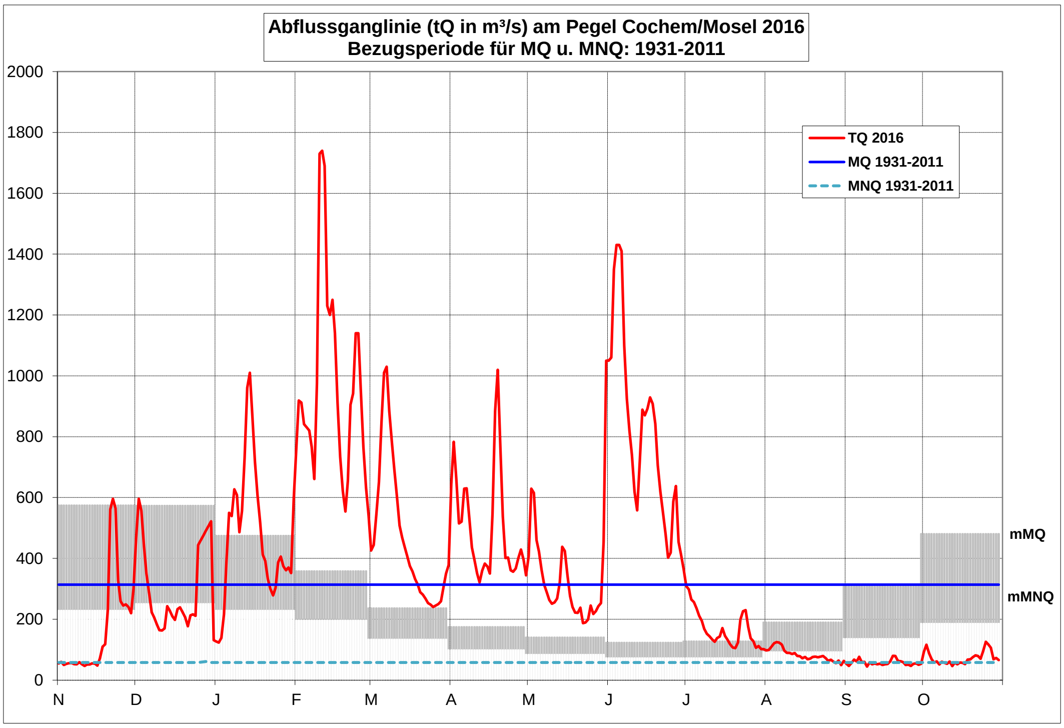


Figure 16: Daily discharge (tQ) at the gauge in Cochem (Moselle) in 2016 in comparison to the long-term averages in m³/s (reference period of MQ, mMQ and mMNQ: period 1931-2011)

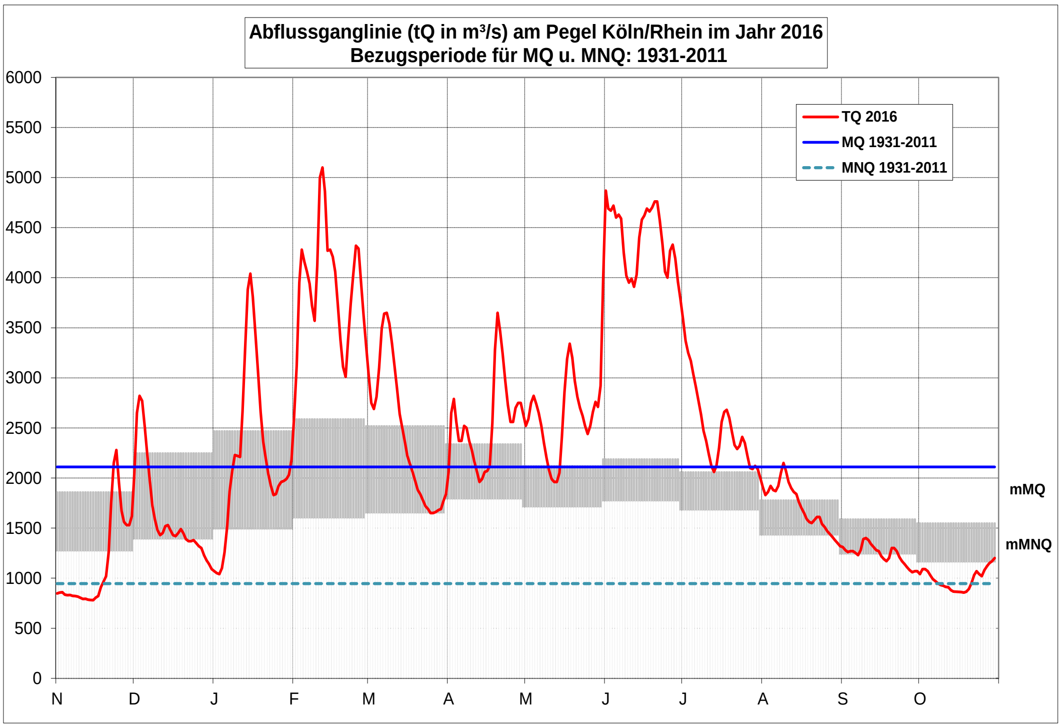


Figure 17: Daily discharge (tQ) at the gauge in Cologne (Rhine) in 2016 in comparison to the long-term averages in m³/s (reference period of MQ, mMQ and mMNQ: period 1931-2011)

Netherlands

The discharge development of the Rhine in the Netherlands was very varied in the last year. The first two months of the year were characterised by subsequent, increased discharge. Spring was average but in June extreme rainfall caused very high discharge for that time of the year. The discharge decreased from July onwards bringing a period of low water levels, which lasted until the end of the year (see Figure 18).

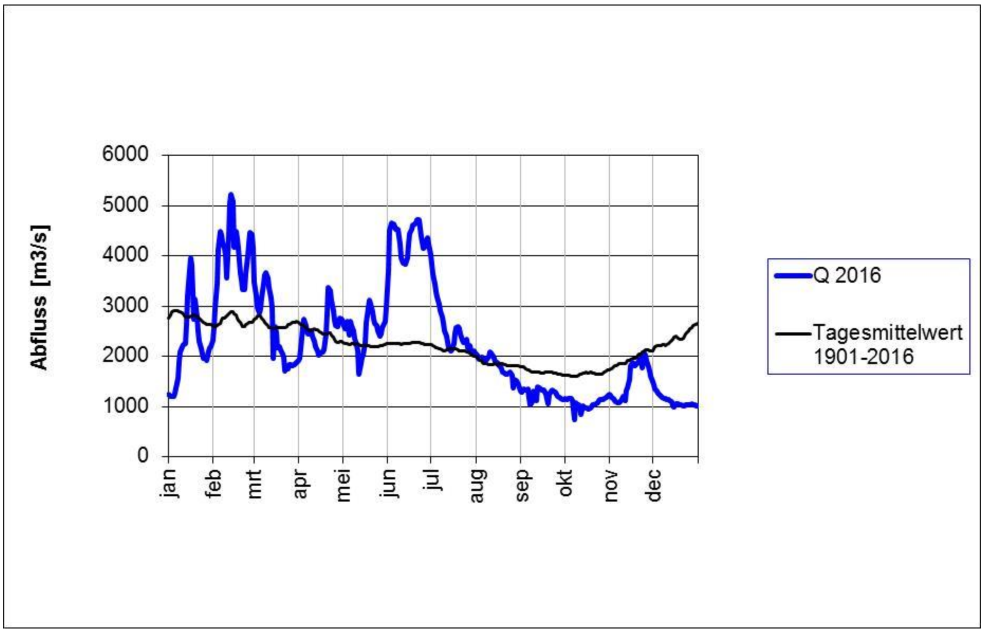


Figure 18: Hydrograph (tQ) at the gauge Lobith (Rhine) in 2016 in m³/s and daily averages: period 1901-2016

The highest water level at the gauge in Lobith in 2016 showed a value of 12.95 + NAP (approx. 5 200 m^3/s) and occurred on 13 February. Water levels were again high in June leading to floods in the southeast and in the centre. Due to dyke forelands at the Rhine being flooded, campsites had to be evacuated, livestock had to be rescued from dyke forelands and events had to postponed or cancelled.

Water temperatures

Austria

The annual average water temperature of Lake Constance was 13.1°C and was, therefore, above the long-term average of 11.9°C by 1.2°C.

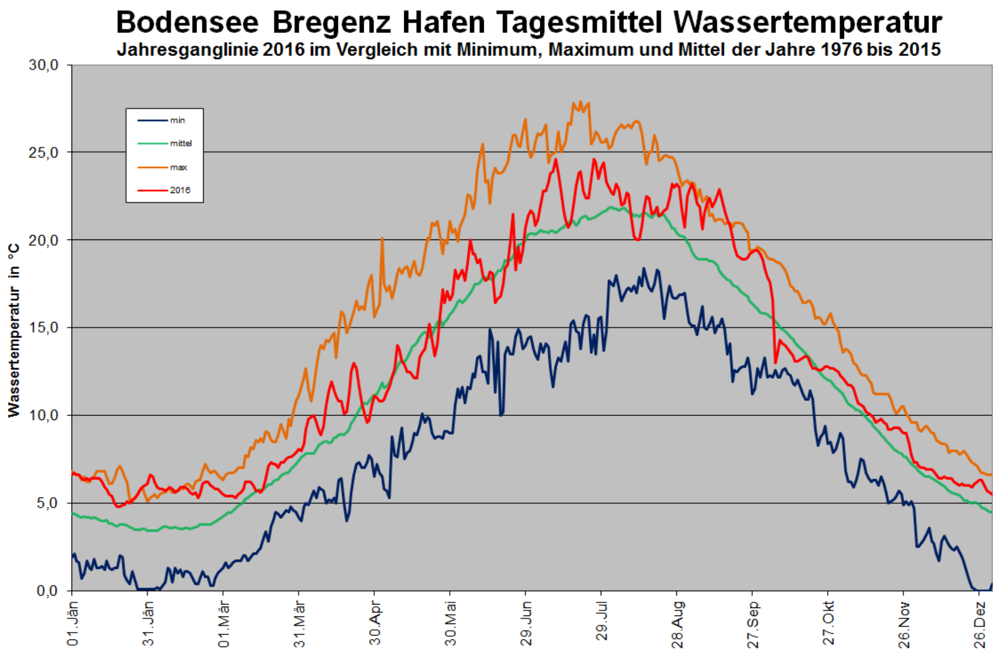


Figure 19: Hydrograph of the water temperature of Lake Constance at the Bregenz gauge in 2016 (red curve) compared to long-term lows, highs and average values of the period 1976-2015.

Switzerland

Overall, the year 2016 was relatively mild in comparison to previous years. Thus, a new high of the annual average temperature of Swiss rivers could only be observed at one FOEN measuring station. This was the case at the station Aare-Brienzweiler, which is influenced by pump storage in its drainage basin. On the other hand, the temperatures were not below the annual lows at any location in 2016.

When reviewing the temperature development of the annual averages during the last decades, we continue to observe a generally increasing trend, e.g., at the FOEN measuring station in Basel. However, the trend is not continuous, but development occurs in stages. This can be seen clearly from the year 1987 onwards, where an increase was observed over two years, followed by a period of no change in around the following ten years. After that, another increase occurred (2000 to 2003) with a subsequent constant phase that lasted at least until 2013.

Winter 2015/2016 was the second warmest winter since records began at the Federal Office for Meteorology and Climatology (MeteoSwiss). The air temperatures are very mild for this time of the year and, as a result, were higher than the monthly long-term averages of the river water temperatures. This was the case at three stations in the midlands and one station in the Walensee area (Linth-Weesen). The monthly averages were exceeded considerably more often in March (ten stations in the midlands and four stations in southern Switzerland). The days when averages were exceeded decreased in March and there was a slight shift from the midlands (three stations) towards the northern Alps (three stations). On occasion, temperatures were also below the long-term minima during these months until May (six measuring stations).

Only the record heat wave at the wave at the end of August and the extremely warm September resulted exceeding of the previous monthly highs on three and 15 occasions, respectively. This was predominately the case for measuring stations in the drainage basins of Lake Geneva and Hochrhein as well as one station in Valais and two locations in Ticino. Other new highs were not observed. The temperatures were below the monthly lows at five stations in the western and eastern central Alps. In December, new minimum values were measured for this month at five stations in the eastern midlands and at one station in the eastern central Alps.

Germany

The average water temperatures (WT) measured for the observation period were 13.6°C at the measuring station Kaub and are below the annual long-term average by 0.3°K. At the gauge in Cologne, temperatures were 13.9°C and below average by 0.1°K. The largest deviation of the monthly averages (below long-term averages) was measured at the measuring stations Kaub and Cologne in May and June with -2.7°K. The largest positive deviation from the monthly averages was measured in December and September in Kaub with +2.3°K and in Cologne with +1.7 and 2.0°K. The maximum negative deviation of daily temperatures was measured in Kaub with -4.6°K in June and at the measuring station in Cologne with -4.7°K at the end of April. Similar to the previous year, the largest positive deviation was +4.1°K in Kaub and +3.5°K in Cologne at Christmas.

The annual development of the daily WT at the selected measuring station showed that the daily averages were slightly above average on two days in February and on occasion considerably below average for the rest of the observation period. September marks an exception, where the averages were exceeded considerably by 2°K on average at both measuring stations.

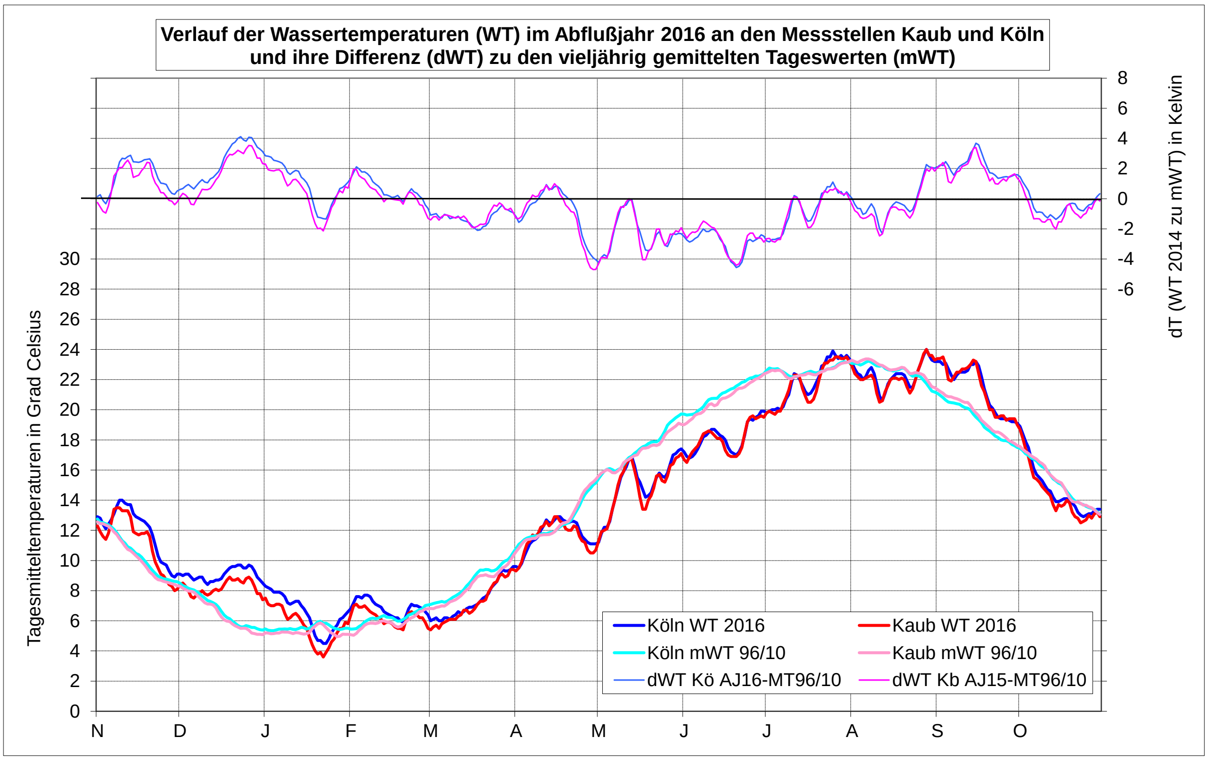


Figure 20: Water temperatures in comparison to the long-term averages

Netherlands

The average water temperatures at the gauge Lobith were 13.7°C and around 0.6°C above the long-term (1961-2016) annual average (see Figure 21). In the order of average water temperatures, the year 2016 takes position 16 (period 1908-2016).

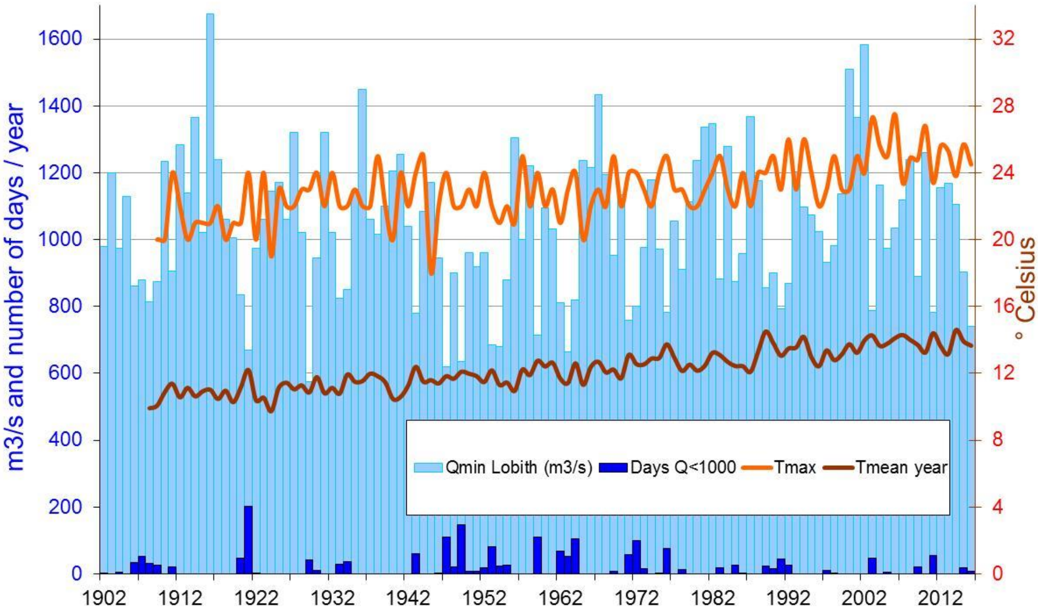


Figure 21: Average and maximum water temperatures in 2016 at the gauge Lobith/Rhine

Groundwater

Austria

The above-average amounts of precipitation during the first half of the year resulted in above-average groundwater levels at most of the groundwater gauges until October. Groundwater levels were mainly below average until the end of the year.

Switzerland

The annual development of the groundwater levels and spring discharges in 2016 in Switzerland can be summarised as follows:

The low groundwater levels and spring discharges increased steadily on the northern side of the Alps after the very dry end of the year 2015 as a result of precipitation in January and February 2016 which was partly very heavy. While around one in four measuring stations in Switzerland showed a low groundwater level or spring discharge in January, the groundwater levels and spring discharges were low only at a few measuring stations in February.

Increasingly high groundwater levels and spring discharges were observed as a result of the above-average precipitation from April to June 2016. Two thirds of all measuring stations showed a high groundwater level or spring discharge. Normal to high groundwater levels and spring discharges with dissimilar tendencies were measured at the beginning of July.

The month July was characterised by high temperatures and some regionally heave thunderstorms. While below-average precipitation totals were measured in Jura, Valais and Ticino, the precipitation totals were above average in central and western Switzerland. However, only unconsolidated aquifers with a small depth to the water table benefited from the localised thunderstorms. August was also warm above average and generally very dry. As a result, the high groundwater levels and spring discharges measured in June went to normal. At the beginning of September, normal groundwater levels and spring discharges with a decreasing tendency were observed in the entire country.

The weather, with small amounts of precipitation in August continued in September and October. As a result of the low precipitation totals, increasingly low groundwater levels and spring discharges were observed in Jura, in the Alps and in Ticino. At the end of October, one third of all measuring stations showed a low groundwater level or spring discharge.

In November, precipitation totals were above average again for the first time since June. Precipitation was mainly snow in areas of higher altitude. Precipitation mainly had an effect on unconsolidated aquifers with a small depth to the water table in the midlands. At the beginning of December, the groundwater levels and spring discharges were largely normal and showed a decreasing tendency.

December in general was uncharacteristically dry in the whole country. Thus, low groundwater levels and spring discharges were observed again at every third measurement station at the end of December.

Suspended sediments

Austria

In 2016 the suspended sediment load at the Alpenrhein at the measuring station Lustenau was higher than the average of the last years by 2.5 million tonnes (approx. 2 million tonnes). The ten-year flood in June contributed almost 40% of the annual load. Thus, June had the highest monthly load with 60% of the annual load.

Germany

To obtain an overview of the suspended sediment loads, data from the measuring stations Maxau (Rhine-km 362.3) were analysed for the upper Rhine, see also Figure 22. For the regions of the middle Rhine/lower Rhine (below the large tributaries), data of the measuring station Weißenthurm (Rhine-km 608.2) used in the last years were analysed. Data for the observation period are not available in sufficient form due to a change in the measurement methods.

Extreme peak values for daily loads are a result of heavy rainfall in summer and the start of the snow melt in winter.

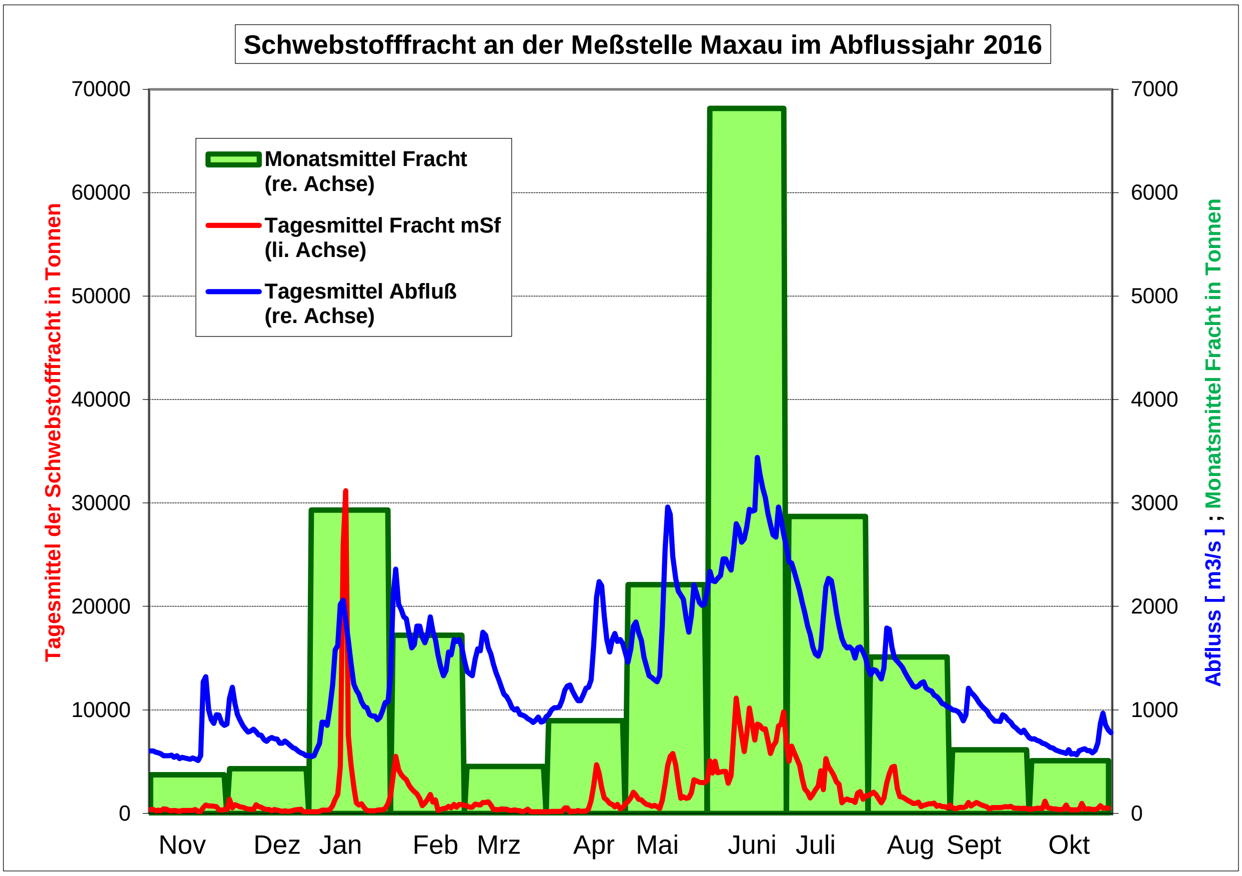


Figure 22: Maxau suspended sediment measuring station, Rhine-km 362.3

The annual suspended sediment load in Maxau was 646 958 t in total, which corresponds to around 51% of the long-term average for the period 1965/2007.

The highest monthly suspended load transport was measured at the measuring station Maxau in June 2016 with 204 445 t (monthly average: 6 815 t), which corresponds to approx. one third of the total annual load. The lowest monthly suspended sediment load was measured in November 2015 with only 11 142 t (monthly average: 371 t).

The daily loads at the measuring station Maxau were at a minimum on 8 April with 107 t compared to an average discharge of 1 240 m³ and at a maximum on 14 January with 31 177 t compared to an average daily discharge of 1 860 m³.

2. Activities of the International Commission for the Hydrology of the Rhine Basin (CHR) in the year 2016

The CHR met twice in 2016, on the 23rd and 24th of March in Halle (Germany) and on the 14th and 15th of September in Salzburg (Austria).

Personnel changes within the CHR
The CHR president, Mr Moser accepted the post of Director of the Department DG 22 - Meteorology, climate monitoring, ground monitoring, aerospace use, German Weather Service within the Federal Ministry of Transport and Digital Infrastructure on 1st March 2016.
Mr Siegfried Demuth accepted the post as Head of the German IHP/HWRP Secretariat in 2016. He takes over from Johannes Cullmann. From 2016, Mr Demuth is the German representative in the CHR.

Activities in CHR projects
Sediment
The CHR supports the project 'From the Source to the Mouth - A Sediment Balance of the Rhine' carried out by the BfG and the University of Aachen. The project was completed at the end of 2014 and the project results were presented in a seminar in March 2015. The project report draft was completed at the end of 2016 and will be published in German language with an executive summary in English within the green CHR series.
After publication of the report, a discussion concerning the knowledge gaps that still exist can be started.

ASG-Rhine: Contribution of snow and glacier melts to the Rhine discharges
The first phase of the project was completed in 2015. The results were presented in a workshop in November 2015.
The final report (in two languages (German and English) was completed in 2016. Furthermore, a synthesis report (extended abstract) was prepared for the project in 2016. The synthesis report (CHR publication I-25) presents the results of the project in a structured and comprehensive way, which makes them accessible to a wide readership.
Different specialist articles were published about the project and the results were presented at several (inter)national conferences.
A potential second phase will focus on the possible future contribution of snow and glacier melts under the influence of climate changes. Discussions regarding the second phase are currently ongoing. The Federal Office for the Environment has already commissioned a number of follow-up studies for Switzerland.

Lake Constance as water reservoir - a literature review
The CHR has commissioned the Technical University Munich to conduct an evaluative-analytical literature review. The concept report of this study was distributed in the internal CHR circle in 2015. A revised version of the study was sent to the CHR representative of the countries with request for comments. Subsequently, the report was sent to all federal states and cantons of the Rhine basin with the request for responses. Publication is foreseen for 2017.

Climate change
The issue of climate change was discussed in detail at all CHR meetings. The CHR intends to start a new project in 2018 as continuation of RheinBlick2050. This project aims to determine the influence of newly available climate projections on the Rhine discharge. There is a con-

nection with the second phase of ASG-Rhine and the new 'Socio-Economy' project to be started.

Socioeconomic influences on the low-water system of the Rhine
After the symposium organised in March 2014, the topic was further discussed in the CHR meetings in 2016.
BfG and Deltares have catalogued the required work hours and prepared a directory of services.
A project preparation group was formed, led by Mr Ruijgh (Deltares). The group's task is to organise workshops, during which fundamental information from different sectors and stakeholders will be initially catalogued and put together.

Hydrological Memory of the Rhine
The CHR intends to start a new project for the collection, optimisation and homogenisation of long-term hydro-meteorological histories. The preparation of such a database is absolutely essential for future projects and especially for a long-term security of the data. Such a common database could lead to an improvement of the scientific work at universities and colleges and can enable the comparability of the results of different studies.

Collaboration with other organisations
The CHR received a request for specialist support for a workshop organised by the Mekong River Commission in Laos on the topic "Water Diplomacy". Mr Grabs represented CHR during this workshop. The final report of the workshop can be downloaded here.

The Huaihe River Commission (China) invited CHR to China for a Huaihe-Rhine workshop. The workshop took place in early 2017.

Events organised by CHR
In March 2015, an international and interdisciplinary symposium on the human evaluation, prevention and management of individual water catastrophes was held in collaboration with the working group for religion pedagogy of the Institute for Catholic Theology at the Martin-Luther-University Halle-Wittenberg. Its title was: 'Water levels rise - humanity is facing catastrophe‘
The title of the symposium (In German: "Land unter - der Mensch vor the Katastrophe") can be interpreted metaphorically and literally: The first part was about humans facing water catastrophe, the management of catastrophes that happen repeatedly and the question of human planning, expectation, processing and strategy development to prevent them as well as coping with them in a technical and moral way. Another part of the symposium addressed the question of human sense of self and interpretation at the time before the next catastrophe that will inevitably happen.
The focus, therefore, was on ‘individual events’, events that can be explained (in hindsight) but do not follow a regular, predictable pattern, which makes it difficult for humans to prevent them.
The symposium proceedings can be downloaded from the CHR website.