The Runoff Regime of the River Rhine and its Tributaries in the 20th Century
Analysis, Changes, Trends

Clear dynamics of change in the course of the 20th century were substantiated within the framework of a comprehensive international study on the runoff regime in the Rhine basin. In the Alpine, High Rhine and Upper Rhine regions the development primarily proceeded in the form of seasonal shifts in runoff, in the northern part of the catchment downstream of the confluence of Main and Rhine mainly in the form of increasing winter runoff. Hence, signals of consequences of climate change already become apparent in the hydrological behaviour of the last 100 years, even if often complemented and superimposed by anthropogenic influences.
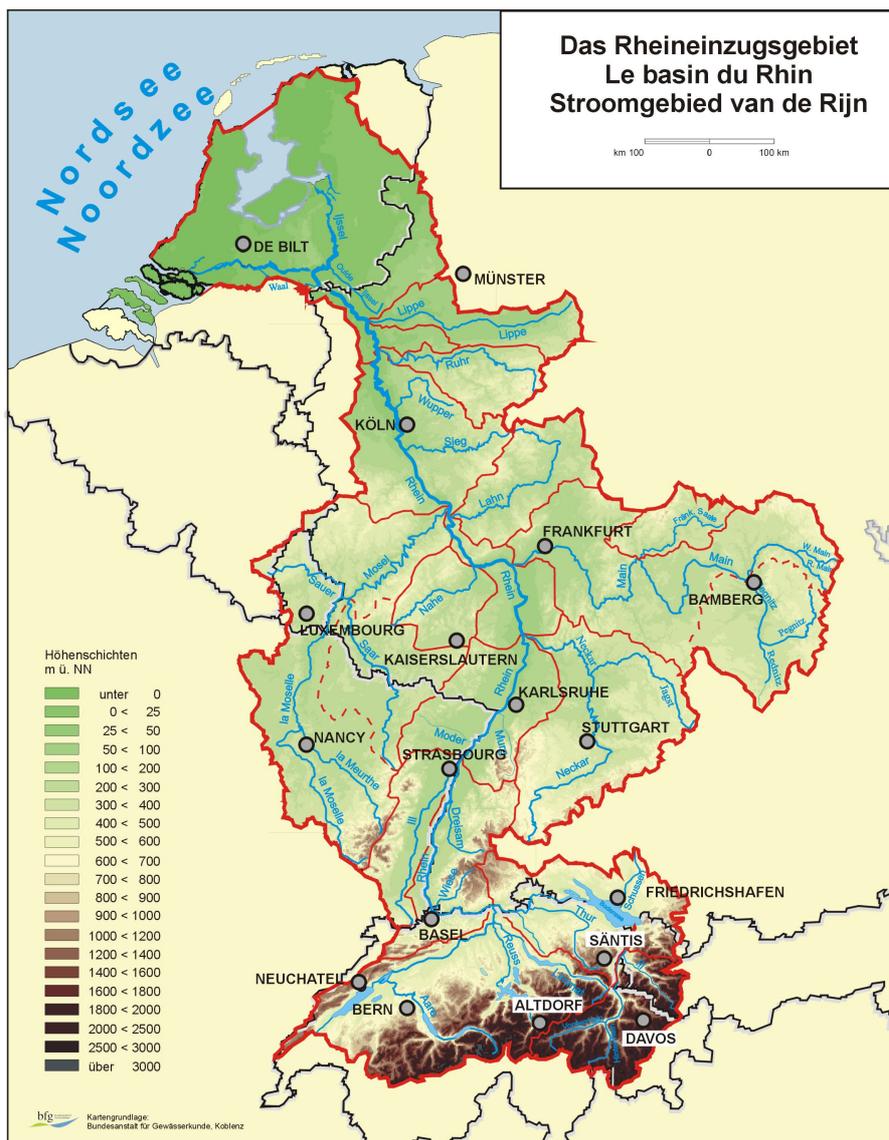
Fig.1   Rhine basin

Task

The Rhine is one of the major European rivers. Its catchment of 185 000 km^2, home to approx. 60 million people, comprises nine states, counting among them a small tip of Italian territory north of Chiavenna, Switzerland, Liechtenstein, Austria, Germany, France, Belgium, Luxembourg and the Netherlands.

About 800 km from Basel to Rotterdam are navigable out of the 1320 km long course of the river. This stretch of the Rhine is one of the busiest waterways in the world, playing a vital role for its riparians in terms of transporting goods. Switzerland, for instance, handles 15% of its foreign trade via the Rhine, with mineral oil products even accounting for 35%.

The main river and its tributaries supply countless industrial plants with process water and also provide numerous thermal power stations, both nuclear and fossil-fuel driven, with cooling water. In water-operated power plants or power plants on reservoirs of the catchment, however, the power of the streaming water does produce a substantial amount of electricity. Furthermore, the Rhine is a major supplier of drinking and process water. Stuttgart and other municipalities in the Neckar region are supplied via lines from Lake Constance, while numerous other cities and communities are provided with river bank filtrate. In the end, the river has to absorb all sewages, albeit cleaned. In spite of these strains imposed by civilisation, "the romantic Rhine" continues to attract tourists from all over the world.

For all these reasons, it is of eminent importance to know if and how the water levels of the Rhine will change in future. Well-founded prognoses, however, can only be made if the processes in the river system are understood. This, in turn, requires a thorough knowledge of the historical development of hydrological parameters.

This is why the International Commission for the Hydrology of the Rhine Basin (CHR) has employed a fifteen-member team that has established a detailed analysis of the changes in the runoff regimes of the Rhine and its tributaries in the 20th century and their potential causes: natural climate fluctuations, anthropogenic climate change as well as direct human interventions such as river regulations and embankments, barrage weirs, reservoirs, water transfers and changes in land use.

The results of the study conducted between 2003 and 2007 are summarized in this brochure. A complete report, published in issue I-22 of the CHR reports, can be ordered from the German IHP/HWRP Secretariat (0261-1306 5435; conde@bafg.de)

The Rhine and its Tributaries – an Overview
On its way from the Alps to the North Sea, the Rhine runs through various landscapes and climate zones impacting on the water level. The two main headstreams, the Vorder and the Hinter Rhine, rise in the mountains of the Swiss canton of Grisons and join south of Chur, forming the **Alpine Rhine** that flows into Lake Constance west of Bregenz. Lake Constance acts as en efficient compensating reservoir. While flood peaks of up to 2500 m^3/s may be reached before entering the lake, peak values at the outlet of the lake are just over 1000 m^3/s.
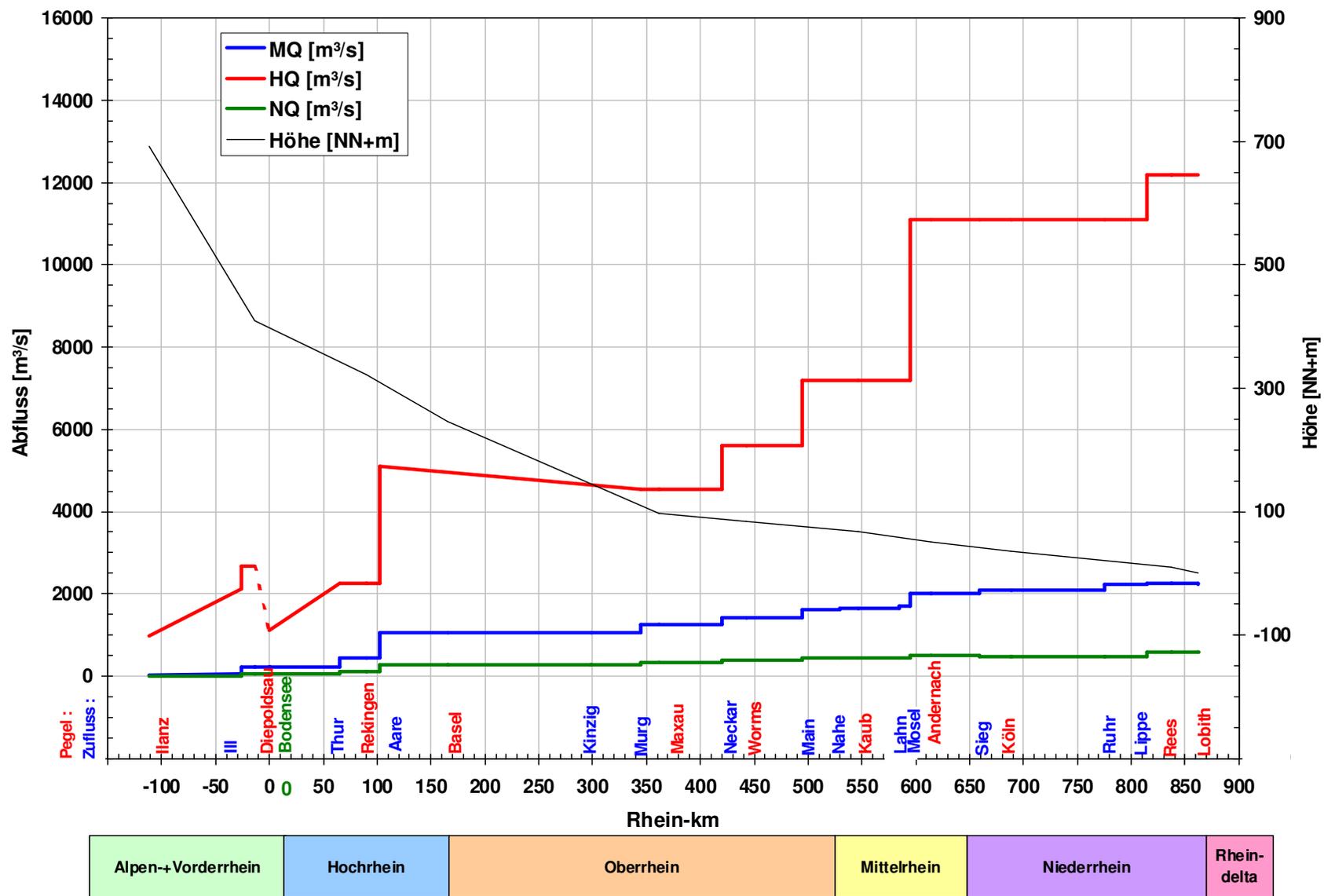
Fig. 2   Hydrological longitudinal profile of the Rhine

The section up to Basel is referred to as **High Rhine**. This is where the Aar river meets the Rhine, near the Swiss community Koblenz, with the Aar river being the major river from a hydrological point of view: its mean discharge of 560 m^3/s (Untersiggenthal gauging station) is one quarter higher compared to the Rhine (440 m^3/s at the Rekingen gauge). Although the combined catchment of Aar river and Rhine at the confluence accounts for just one fifth of the catchment at the Lobith gauging station on the German-Dutch border, the mean discharge of 1000 m^3/s almost reaches half of the Lobith value. This fact illustrates the impact of the Alps on the Rhine's water level.

The **Upper Rhine** commences at Basel. The inflows from the Black Forest and the Vosges increase mean discharge in total by 190 m^3/s. The rivers Neckar and Main, contributing on average 135 m^3/s respectively 210 m^3/s, are by far the most important tributaries on the long stretch to Bingen.

From Bingen to Bonn the **Middle Rhine** breaks through the Rhenish Slate Mountains in a valley incised up to 200 m deep. At the German town of Koblenz, the Moselle river joins the Rhine, raising the mean discharge at the Andernach gauge by averagely 315 m^3/s to 2010 m^3/s.

The **Lower Rhine** begins in Bonn. Until reaching Lobith, the tributaries increase the mean discharge by further 210 m^3/s to 2220 m^3/s. Subsequently, there are no more inflows into the Rhine, which branches into the arms of the delta.

The Runoff Regime of the Rhine
The flow of a watercourse – whether small brook or large river – strongly depends on the amount of precipitation in the catchment. The water volume that is not lost to evaporation or plant transpiration eventually runs off; fluctuations in runoff are controlled by the temporal distribution of precipitation and evaporation. If precipitation falls as snow, it is released with a time delay when melting or stored as ice in glaciers for even longer periods of time.

In a nutshell, "runoff regime" means the intraannual runoff of a stream to be regularly expected. A method developed by the French hydrologist Pardé (1893 – 1973) has become established to describe the runoff fluctuations as a characteristic feature of the runoff regime. The so-called Pardé coefficient is formed from the ratio between monthly runoff and annual runoff of a catchment (in each case averaged over many years).The graphic representation provides a characteristic curve. Being dimensionless, the Pardé coefficient allows a comparison of watercourses having varyingly large runoff volumes. The following types of runoff regimes prevail in the Rhine basin (cf. fig. 3):

The **nival regime** (e.g. Ilanz gauge), characterized by snowfall and snowmelt, is extremely dominant in the Alps with a steep runoff peak in early summer and very low values in winter. The river Aare is also characterised by a nival regime, in its lower reaches however being strongly subdued owing to the impact of the lakes in the Swiss Midlands.
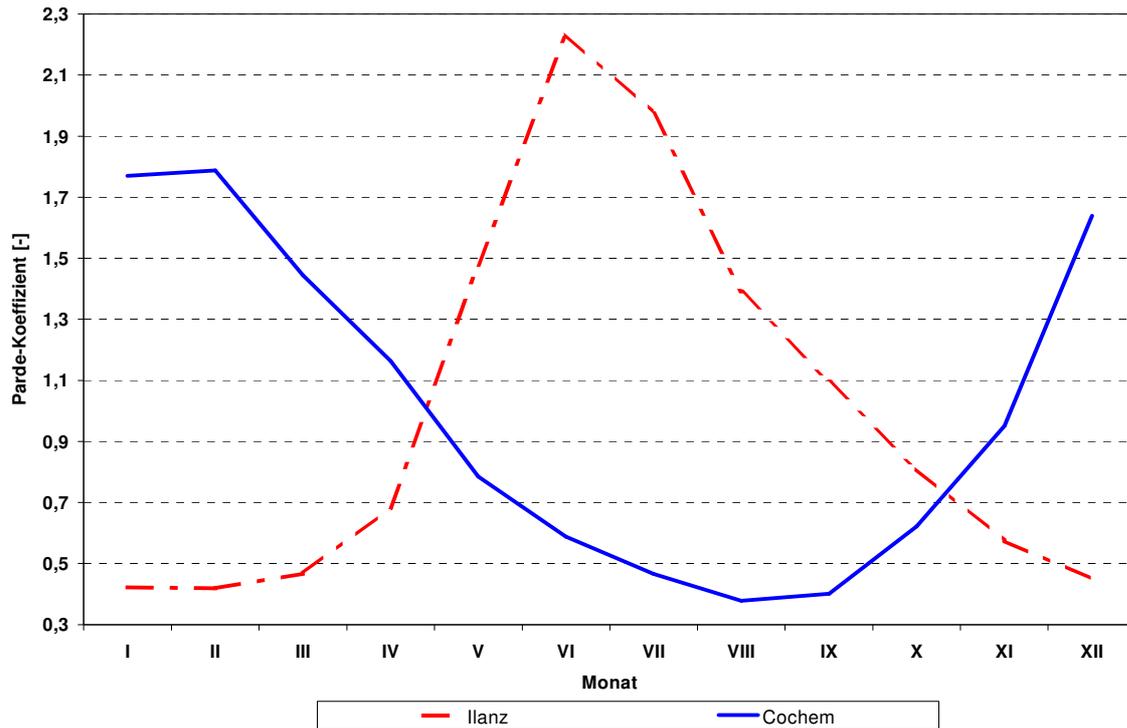
Fig. 3   Characteristic types of runoff regimes in the Rhine basin: Illanz gauging station (nival / Vorder Rhine), and Cochem (pluvial / Moselle), reference period 1951-2000

The major tributaries in Germany, i.e. Neckar, Main and Moselle (e.g.: Cochem gauging station), consistently show a **pluvial regime**. Due to the distribution of rainfall and the seasonal differences in evaporation intensity, mean runoff reaches its maximum in the winter months and its minimum in August and September.

As the river proceeds, the runoff regime of the Rhine reflects the natural and man-made impacts resulting from its gradual catchment expansion. In the process, none of the joining tributaries succeeds in imposing its own regime character on it – but the plethora of feeding rivers downstream increases the complexity of the runoff regime in the Rhine.

Owing to the dominant alpine influence, the Basel Rhine gauge (cf. fig. 4) shows a typical nival regime, that is superimposed by tributaries with a pluvial character further downstream. As these tributaries bear significantly less water than the Rhine, the nival basic character of the Rhine regime continues to exist up to the confluence with the Main river. It is not before reaching the Middle Rhine that the rivers Main and Moselle eventually cause major changes. From the Andernach gauging station onwards, pluvial elements prevail. Now the highest runoff occurs in February, the lowest in September.
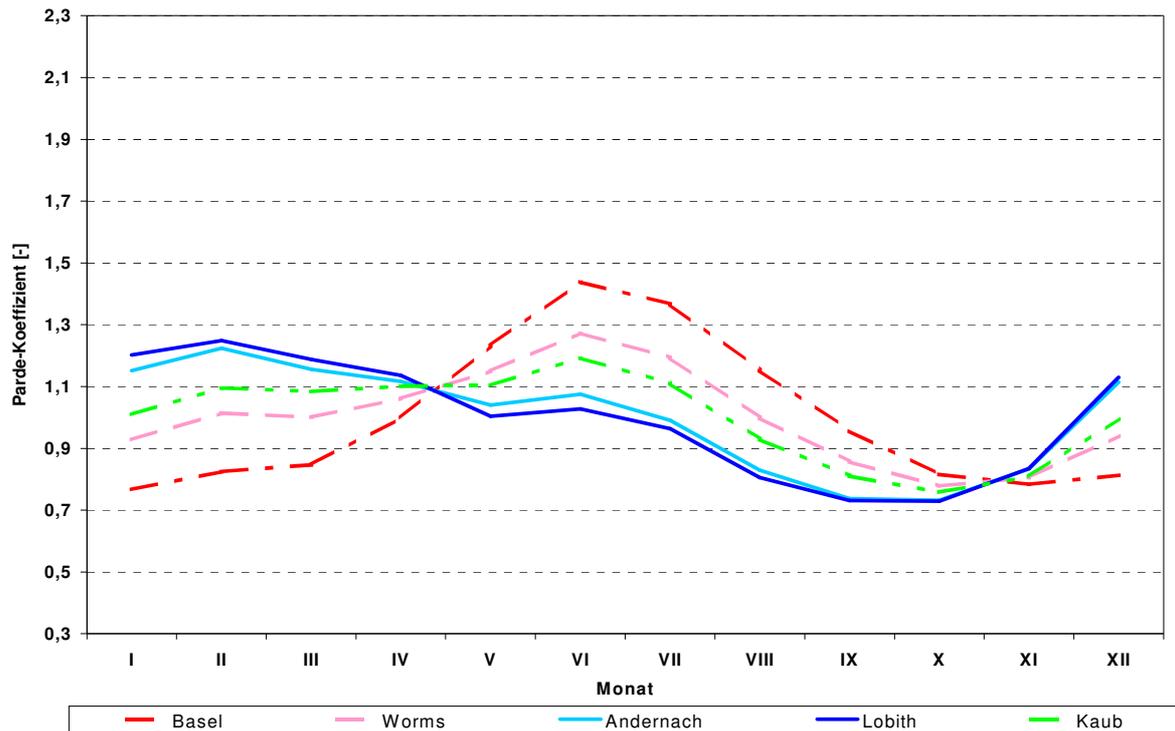
Fig. 4 Catchment-induced change of the runoff regime of the Rhine in the course of the river using the example of the gauging stations at Basel (Upper Rhine), Maxau (Upper Rhine), Kaub (Middle Rhine), Andernach (Middle Rhine) and Lobith (Lower Rhine); Reference period 1951-2000

Data Collection and Data Analysis

To record the heterogeneity in the Rhine basin, it has been subdivided into 38 sub-catchments, each of these represented by one gauge that continuously registers the daily discharge means, at least since 1951. 16 of the so-called main gauges on the Rhine and on major tributaries have already been supplying these values since 1901 or 1904.

Although the time series are available in proven form, a review has revealed discrepancies. For eight main gauges – i.e. Maxau, Worms, Kaub, Andernach and Cologne on the Rhine, Würzburg on the Main as well as Cochem on the Moselle river – the inconsistencies found could be removed following thorough data analysis.

Analogous to runoff, areal precipitations in the 38 catchments were calculated on a daily basis and aggregated into monthly, semi-annual, annual and decadal values using weather station data.

The hydrological and meteorological parameters were entered into a data base. Subsequently, the following time series were established for each catchment:
- Daily runoff means (tQ);
- Mean monthly, semi-annual and annual discharge (MQ);
- Lowest arithmetic mean discharge of 7 or 21 consecutive days within one year or one half-year (NM7Q or NM21Q);
- Flood peaks according to years and half-years (HQ);
- Flood volumes, i.e. the annual or semi-annual totals of all flood events exceeding a certain threshold value;

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- Precipitation totals (SumhN) on monthly, semi-annual, annual and decadal basis;
- Maximum monthly precipitations.
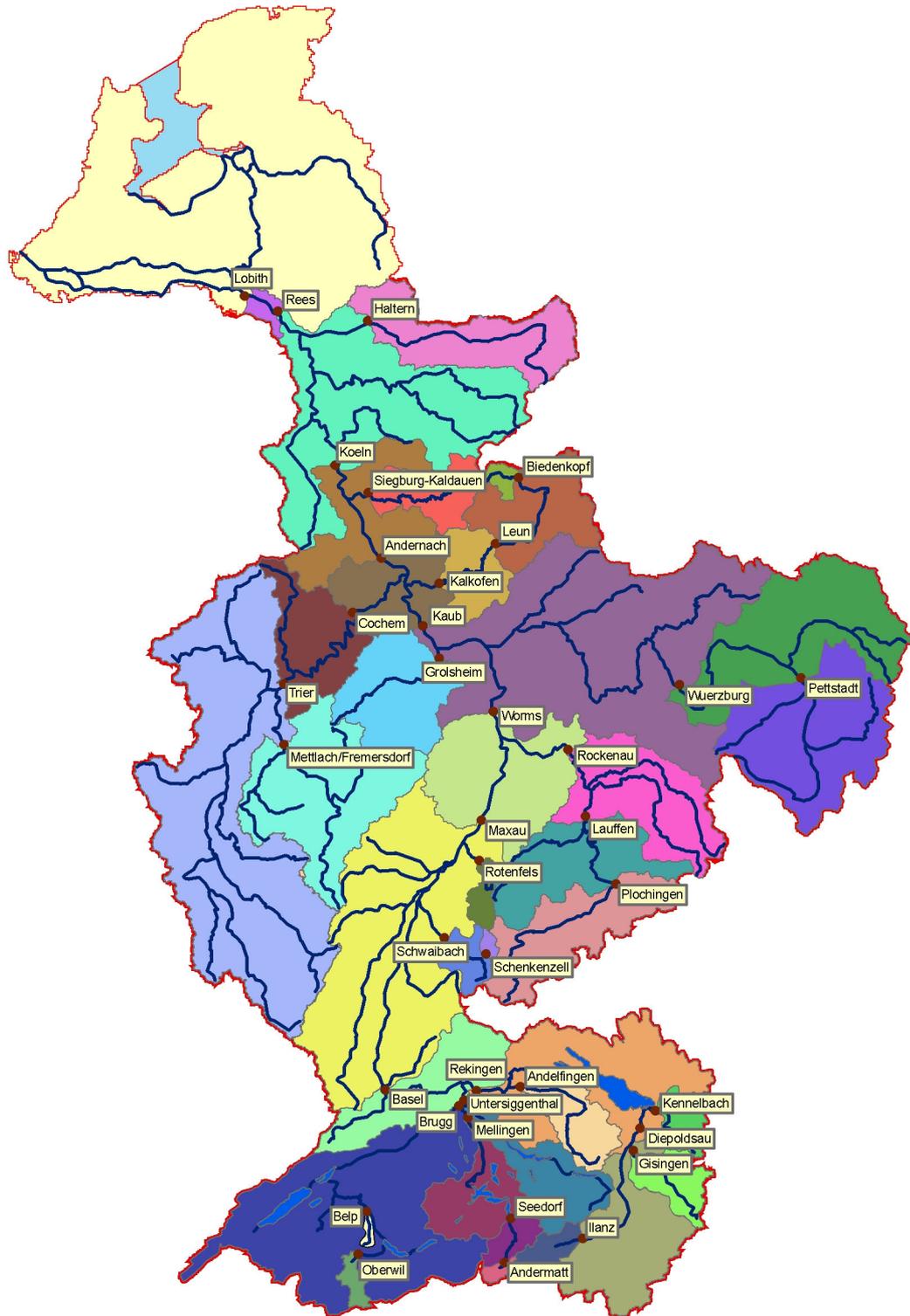
Fig. 5   The 38 sub-catchments of the study including the gauges considered

In addition to this, semi-annual, annual and decadal means of air temperature as well as the annual and decadal potential evaporation heights were gathered.

To visualize developments within the time series, they have been analysed using statistical methods. To identify existing developments, jump analysis and trend analysis have been of special importance (for relevant examples cf. Fig. 6).
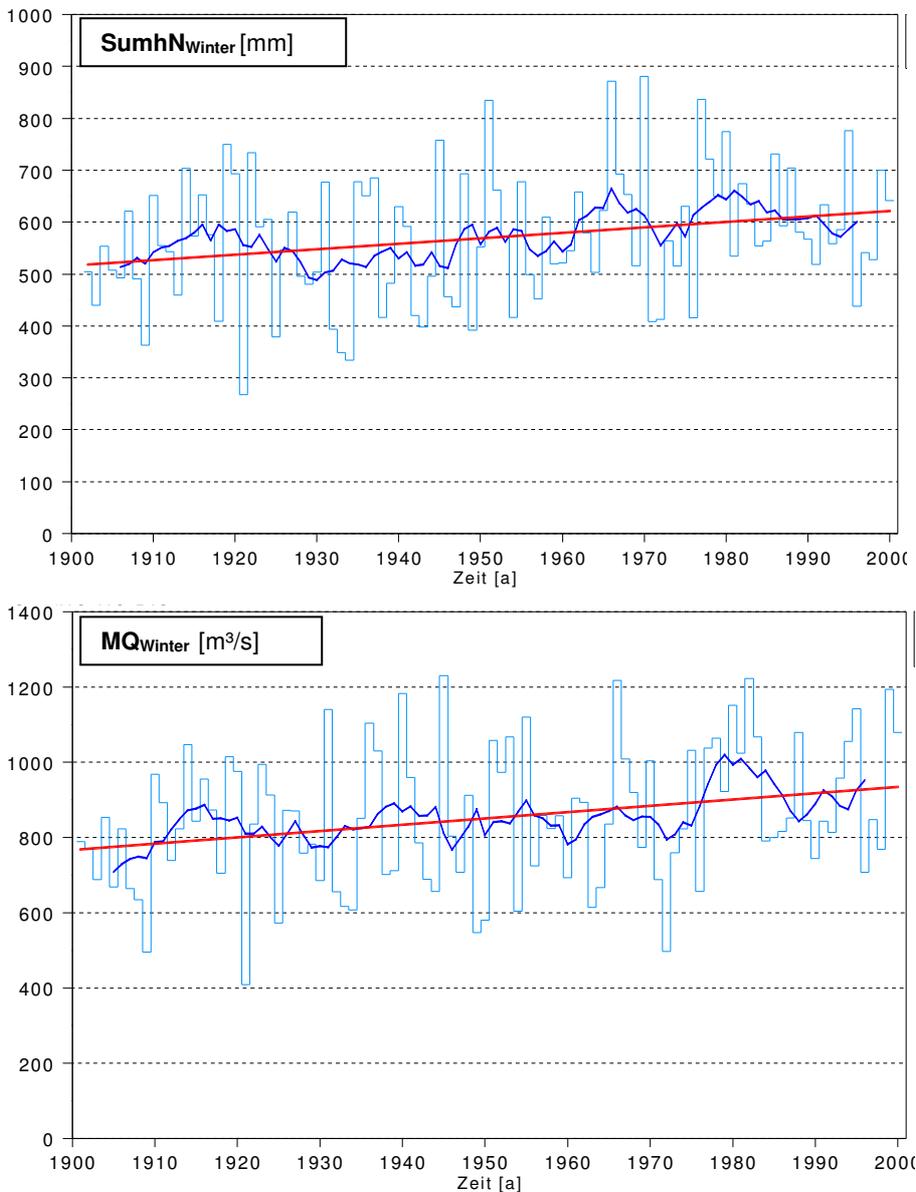
Fig. 6   **Examples of trend analyses performed: development of SumhN (Areal precipitation totals / top) and MQ (mean runoff / bottom) in the sub-basin up to Basel; for winter half-years each**
    —— **Blue, bold: 9-year running average**   —— **red: trend (FQS)**

The trend analyses were performed using the widespread total least squares method (FQS). Additionally, the results were always tested for significance. Given the varied significance of the trend results, these were classified into three levels:
   - tendency, a statistically still unproven development
   - trend, a statistically proven development (at least 80% significance)
   - strong trend, a statistically well-founded development (at least 95% significance)

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Climate in the 20th Century
Temperature
In the course of the 20th century, temperature in the Rhine region increased by 0.8 °C on an annual average. The rise was stronger in the hydrological winter half year (November - April) than in the summer half year (May - October), i.e. 0.9 °C compared with 0.7 °C (cf. Fig. 7). In keeping with the global trend, the years between 1990 and 2000 have been the warmest in the 20th century in the Rhine region.
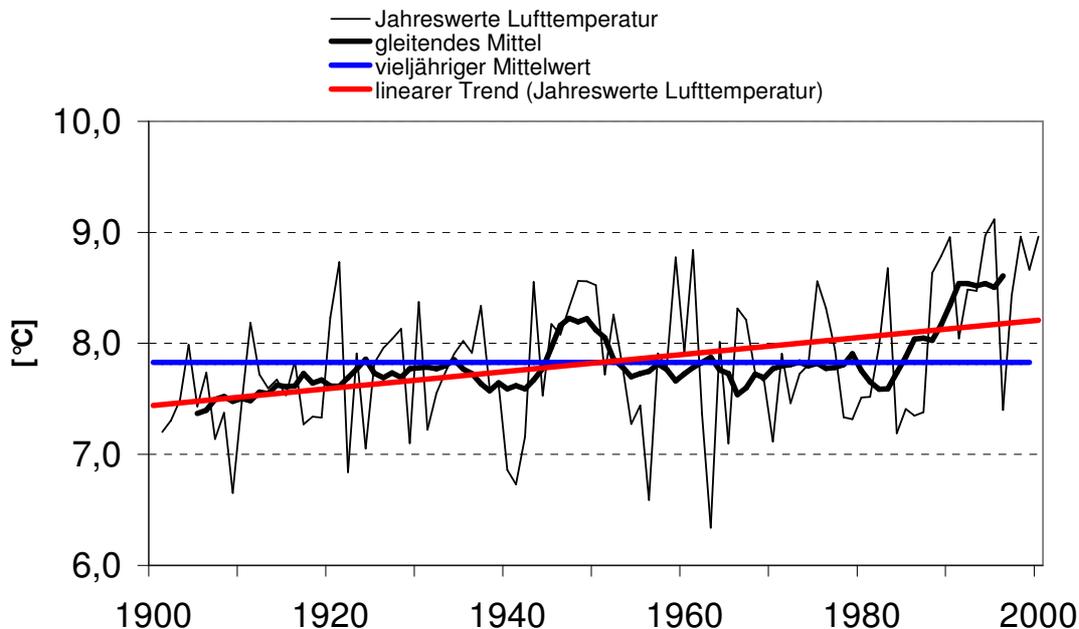
Fig. 7   Air temperature 1901 – 2000 in the Rhine region

A detailed analysis reveals that temperature rise in winter is related to altitude and moreover differs depending on the month. It is strongest in altitudes up to 500 metres, while only minor increases, especially in February and March, are noticeable at high altitudes. August is the summer month featuring the strongest rise in temperature with the same dependency on altitude as in winter.

Higher winter temperatures naturally impact on the snow cover. Hence it was found that the number of days with a permanent snow cover below 1300 m altitude decreased in Switzerland towards the end of the 20th century.

Precipitation
In the entire Rhine region, precipitation increased between 1901 and 2000. This is primarily due to higher precipitation rates in winter. From Basel to Lobith, all sub-catchments represented by Rhine gauging stations, show a strong rising trend. Similar developments can be discerned in the tributaries. Summer, however, hardly shows any changes (cf. trend pictograms in Fig.8).

The developments are associated with changes in the general weather situation. In the second half of the 20th century, so-called „western weather situations" bringing moist Atlantic air into the region, have increased in winter and spring. Weather in the summer season has developed in a similar direction. Since 1950, by contrast, high-pressure situations with low precipitation have occurred far less frequently than in the previous decades. Given that the formation of precipitation during this season is

more complex than in winter, no clear impact on the development of precipitation can be discerned; a great number of these processes is still being investigated by climate research.

	Series 1902 - 2000 SumhN			Series 1951 - 2000 SumhN		
	Year	Wi.	Su.	Year	Wi.	Su.
Lower Rhine						
Lobith						
Rees						
| Lippe Haltern						
Köln						
| Sieg Siegburg						
Middle Rhine						
Andernach						
Mosel Cochem						
Lahn Kalkofen						
Kaub						
Nahe Grolsheim						
Upper Rhine						
| **Main Würzburg**						
Worms						
| **Neckar Rockenau**						
Maxau						
| Murg Rotenfels						
| Kinzig Schwaibach						
High Rhine						
Basel						
Aare Untersiggenthal (1905-2000)						
Aare Brugg						
Reuss Mellingen (1905-2000)						
Rekingen (1905-2000)						
Thur Andelfingen (1905-2000)						
Alpine Rhine						
Diepoldsau						

Legend:
- downward tendency
- downward tendency (80% significance)
- downward tendency (95% significance)
- upward tendency
- upward tendency (80% significance)
- upward tendency (95% significance)
- no data

Fig. 8 Precipitation trends and tendencies for sub-catchments

Development of Mean Runoff
Alpine and High Rhine
Excepting one case, the annual mean runoff values in the 14 sub-catchments on the Alpine and High Rhine do not display any directed development. Only a review separated into hydrological summer and winter half-years reveals changes. Winter runoff increases in seven regions, while summer runoff concurrently decreases in five regions. The Basel gauging station shows a clear trend in this regard for the relevant period.

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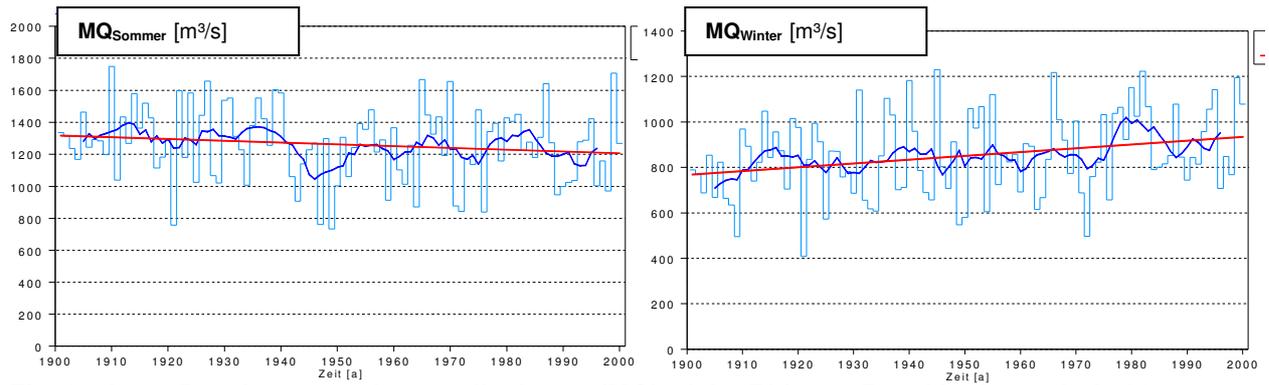
Fig. 9a, b. Development of mean discharge (MQ) of the Rhine at Basel in the period 1901-2000 in the summer and the winter half-years

blue, bold: 9-year running average   red: trend (FQS)
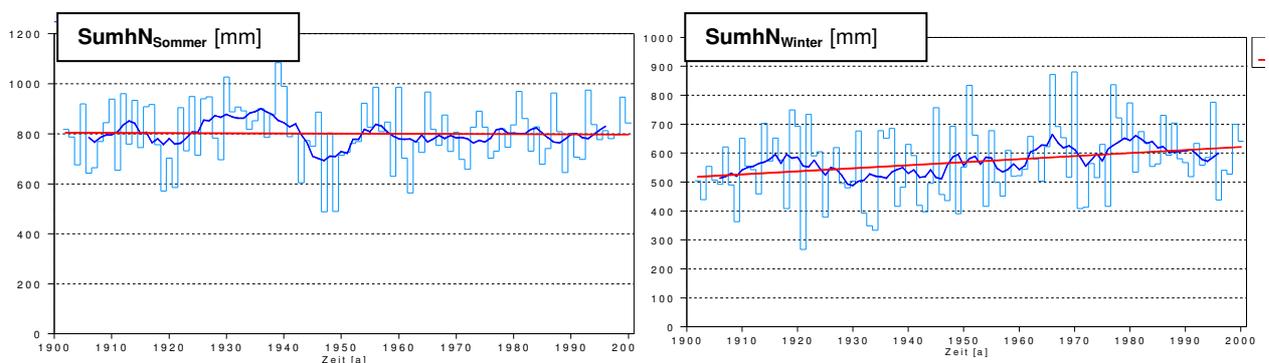
Fig. 9c, d. Precipitation development in the Rhine region up to Basel in the period 1901-2000 in the summer and winter half-years

blue, bold: 9-year running average   red: trend (FQS)

The rise in winter runoff is accompanied by an increase in precipitation; the decreasing runoff in summer, on the other hand, is not faced with a similar decrease in precipitation values. They have remained constant.

Hence the changes in runoff cannot merely be explained by precipitation development; rather, there must be other instrumental effects. Due to the temperature rise in winter, more precipitation falls as rain rather than snow, i.e. there is no interim storage, but immediate runoff. Furthermore, thaw weather conditions repeatedly cause the runoff of snowmelt. Thus, in winter, more surface water runs off, which is then no longer available in the next early summer. Moreover, anthropogenic impacts are added to this.

Over time, primarily in the Alpine region, reservoirs were built with a total storage capacity of 1.9 billion m^3 in the catchment upstream of Basel (table 1).

The reservoirs are mainly used to produce electricity, entailing a typical, homogeneous management: in early summer, when the tributaries carry a lot of water, the reservoirs are filled to allow running the turbines in winter, during low-flow, by using the stored water

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Table 1   Reservoirs in the Rhine region

Rhine segment or tributary	Volume [hm³]	Total volume [hm³]
Vorder Rhine	253.14	253.14
Hinter Rhine	289.36	542.50
Tamina	38.50	581.00
Ill (A)	183.40	764.40
Bregenzerach	8.40	772.80
Lake Constance	1.40	774.20
Thur	0.60	774.80
High Rhine (CH)	7.26	782.06
Aar river	496.95	1279.01
Reuss	153.19	1432.20
Limmat	314.86	1747.06
High Rhine (D)	112.85	1859.91
Upper Rhine	27.63	1887.54
Ill (F)	24.29	1911.83
Neckar	37.99	1949.82
Main	59.64	2009.46
Nahe	14.05	2023.51
Lahn	6.63	2030.14
Moselle (F)	103.58	2133.72
Moselle (D)	50.53	2184.25
Sauer	71.40	2255.65
Wied	4.45	2260.10
Ahr	0.73	2260.83
Sieg	123.10	2383.93
Wupper	140.43	2524.36
Erft	51.00	2575.36
Ruhr	496.06	3071.42
Lippe	50.01	3121.43

Without having knowledge of relevant management plans, the shift in runoff cannot be quantified precisely, but a rough estimate can give an idea of the dimension involved. The cautious assumption that half of the storage volume of 1.9 billion m³ runs off in the six winter months, implies an increase of discharge by 60 m³/s in this period at the Basel gauging station as well as a corresponding decrease in summer.

The effect can be easily substantiated by comparing the runoff hydrographs of the years 1920 and 1995 (Fig. 10) at the Diepoldsau gauge in the Alpine Rhine. In 1920 there was still no major reservoir in the catchment, by 1995 a storage volume of 764 million m³ had been created. Although the selected years were subject to similar weather conditions, their hydrographs differ significantly. Winter low flow is increased, summer runoff reduced, while runoff is distributed more regularly over the year.
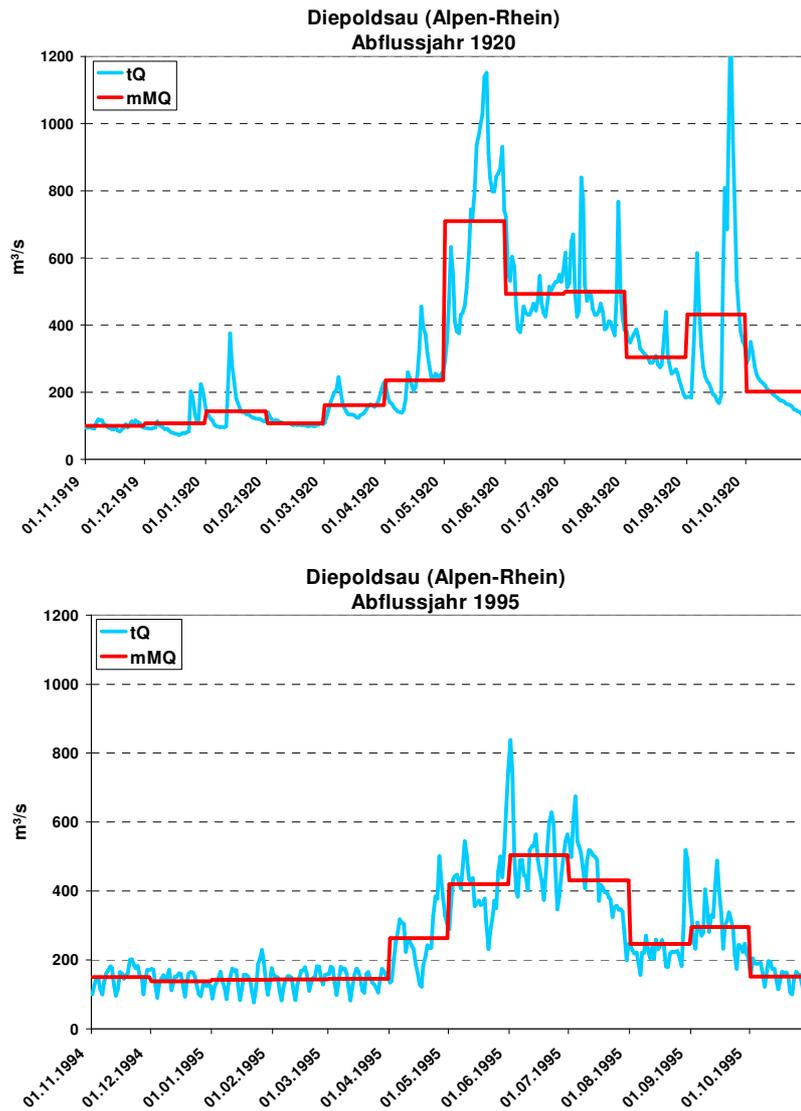
Fig. 10 Runoff hydrograph at the Diepoldsau gauge, comparison of years 1920 and 1995

The effect of storage management is additionally confirmed by an analysis of catchments lacking reservoirs also performed as part of the study: Here, the shift between summer and winter is much less pronounced.

To comprehend the impact of **glacial recession,** a catchment upstream of the Ilanz gauge has been exemplarily investigated. Here, the glacial surface has receded from 68.5 km^2 to 21 km^2 between the years 1850 and 2000. Based on certain assumptions, a reduction of the volume from 1.8 km^3 to 0.45 km^3 can be calculated. The lost ice volume corresponds to a total released water equivalent of 1.16 km^3, accounting for an additional runoff of 0.75 m^3/s in the four main months of glacier melt from June to September. Transferring the results from Ilanz to the entire catchment upstream of Basel having a twenty times higher glacial surface, an increase of runoff by 15 m^3/s is to be expected in this period, i.e. merely 1.2% of average runoff in August. This figure illustrates that the so-called „glacial recession" phenomenon only has a marginal influence on the mean streamflow of the Rhine.
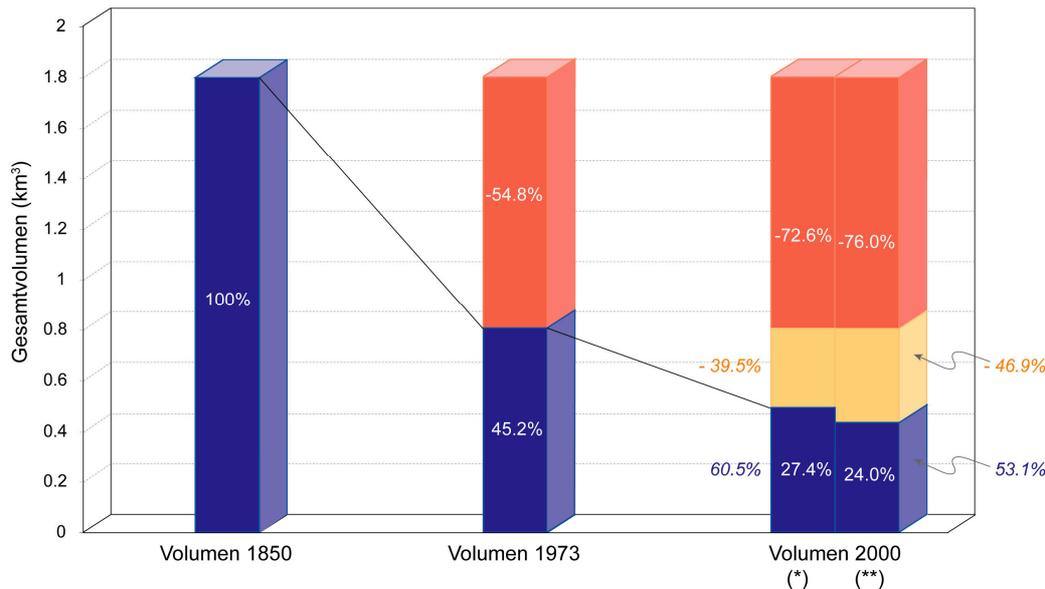
Fig. 11   Sub-catchment Ilanz – development of glacier volume, period 1850-2000
Method of calculation: * MAISCH (1992)   ** Driedger & KENNARD (1986)

The above statements on the effects of climate change on glacial runoff resulting from volume balance analyses in glaciers, do not yet allow giving answers to questions related to the overall share of glacier water in the Rhine's runoff. These questions are currently the subject of research work.

Upper Rhine
The runoff in the Upper Rhine is determined by the hydrological conditions of the High Rhine. Reservoir management, causing a redistribution of runoff from summer to winter up to Basel, is irrelevant here, in view of the fact that the entire storage volume allocated to this river segment is only 150 million m^3.

The tributaries from the Black Forest and the Vosges as well as the Main and Neckar rivers are to be assigned to the pluvial type. Due to higher precipitation in winter, their mean runoff increases considerably in this season, entailing a further rise in runoff in the Rhine.

Although precipitation stagnates in summer in the Neckar and Main basins, runoff increases owing to transfers of water from other catchments. Since the middle of the 20th century, water from Lake Constance, the Danube and the western Black Forest has been supplied to the agglomeration between Stuttgart and Heilbronn. It is eventually the river Neckar that benefits from this water in the form of wastewater. This water transfer has been amounting to 200 million m^3 per year since the 1980s, with the accruals of the Main ranging in a similar scale. 125 million m^3 water are annually transferred from the Danube via the locks in the Rhine-Main-Danube-Canal and further 25 million m^3 from the Altmühl river into the catchment of the Main. The summer increase in runoff in the rivers Neckar and Main causes the slight decrease in summer runoff still noticeable at Maxau, to become inverted into a slight increase (cf. table 2).

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Table 2 Changes in mean discharge (MQ) at selected gauges in the Upper and Middle Rhine region

	Change MQ$_{year}$		Change MQ$_{summer}$		Change MQ$_{winter}$	
	%	m³/s	%	m³/s	%	m³/s
Maxau (Rhine)	7.0	87.6	-0.5	-10.3	16.5	176.0
Rockenau (Neckar)	23.0	27.8	24.0	20.8	22.5	34.9
Worms (Rhine)	7.5	104.0	1.5	22.1	14.5	186.0
Würzburg (Main)	31.5	31.8	25.5	16.9	38.5	46.9
Kaub (Rhine)	9.5	152.0	2.5	44.2	16.5	261.0

Middle and Lower Rhine

The Middle Rhine begins downstream of the confluence of the Main and Rhine rivers near Bingen. Among the local tributaries, it is the Moselle river – whose catchment is dominated by an Atlantic influenced climate - that makes a major impact on the Rhine. Mean precipitation is 900 mm, with peak values of 1800 mm being reached on the western slope of the Vosges mountains. In the entire Moselle basin, precipitation has increased in the winter half-year, reflects as rise in mean discharge from 420 to 500 m³/s at the Cochem gauging station. In summer, only minor changes can be noticed.

Similar trends can be observed in most other tributaries of the Middle Rhine and even in the Rhine, e.g. at the Andernach gauge, downstream of the confluence with the Moselle river (cf. Fig. 12).
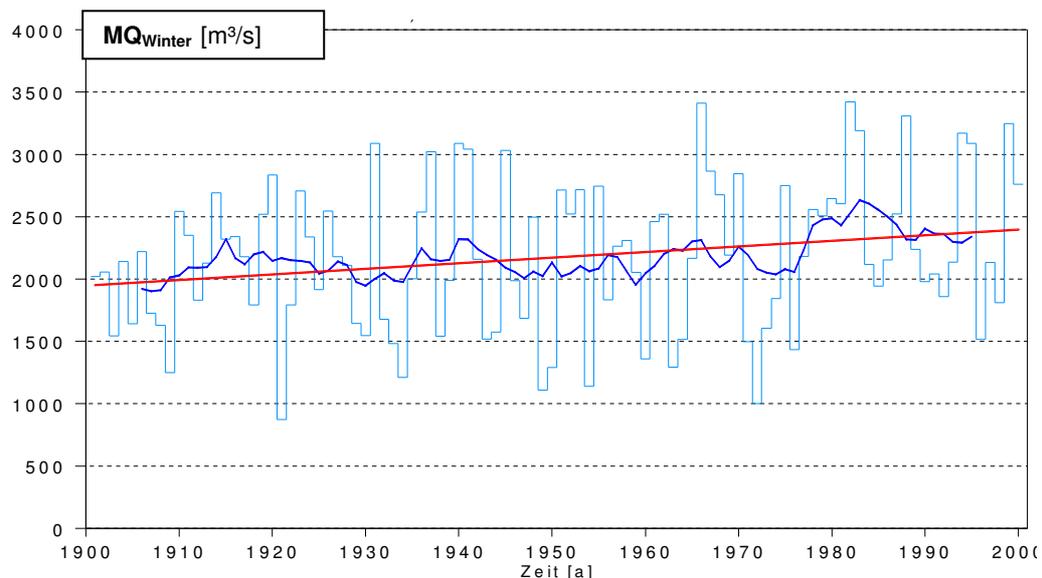
Fig. 12:   Gauge Andernach/Rhine – Mean discharge (MQ) of winter halfyears, period 1901-2000

——— blue, bold: 9-year running average   ——— red: trend (FQS)
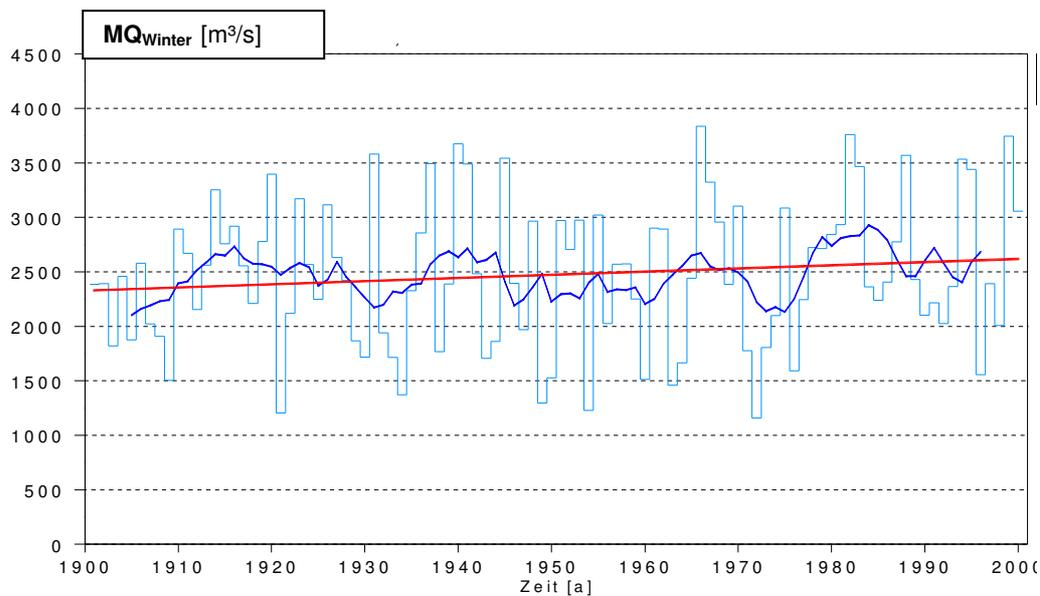
Fig. 13: **Gauge Lobith/Rhine – Mean discharge (MQ) of winter halfyears, period 1901-2000**
blue, bold: 9-year running average **red: trend (FQS)**

Until reaching the Lobith gauging station on the German-Dutch border (cf. Fig. 13) the Rhine does receive a number of tributaries that have been fundamentally changed due to anthropogenic interference. Second to the Alps, the largest storage volume in the Rhine basin, overall 810 million m^3, is concentrated on the rivers Ruhr (500 million m^3), Sieg, Wupper and Erft. The reservoirs are not primarily used for power production. In fact, they are multifunctional, serving several purposes such as drinking water supply, low-flow augmentation, flood protection and aquatics. This implies management plans with differing hydrological impacts that are eventually neutralized.

Reihe 1901 - 2000	MQ		
	Jahr	Wi.	So.
Niederrhein			
Lobith			
Rees			
Köln			
Mittelrhein			
Andernach			
Cochem Mosel			
Trier			
Kaub			
Oberrhein			
Main **Würzburg**			
Worms			
Maxau			
Hochrhein			
Basel			
Untersiggenthal(1905) Aare			
Mellingen(1905)/Reuss			
Seedorf (1905)/Reuss			
Rekingen (1905)			
Andelfingen(1905) Thur			

Legend:

	Trend fallend	80% Signifikanz
	Trend fallend	95% Signifikanz
		keine Signifikanz
	Trend steigend	80% Signifikanz
	Trend steigend	95% Signifikanz

Fig. 14 **Synoptic pictrogram of the trend of mean discharges at the major gauges in the Rhine basin in the 20th century**

The synopsis in figure 14 clearly shows the spatial differentiation:
- On the one hand, seasonal redistribution processes prevail in the southern Rhine basin, while runoff volumes are nearly unchanged on an annual basis.
- On the other hand, increased runoff is observed in the river basin north of the confluence with the Main river, eventually due to a rise in winter precipitation.

Flood

In the course of the 20th century, flood peaks have increased in the alpine and prealpine Rhine basin (excepting Ilanz due to construction and operation of reservoirs). This trend continues beyond the Basel gauge (Fig. 15) into the Upper Rhine. Similar tendencies as in Basel can be observed at the gauges of Maxau and Worms.
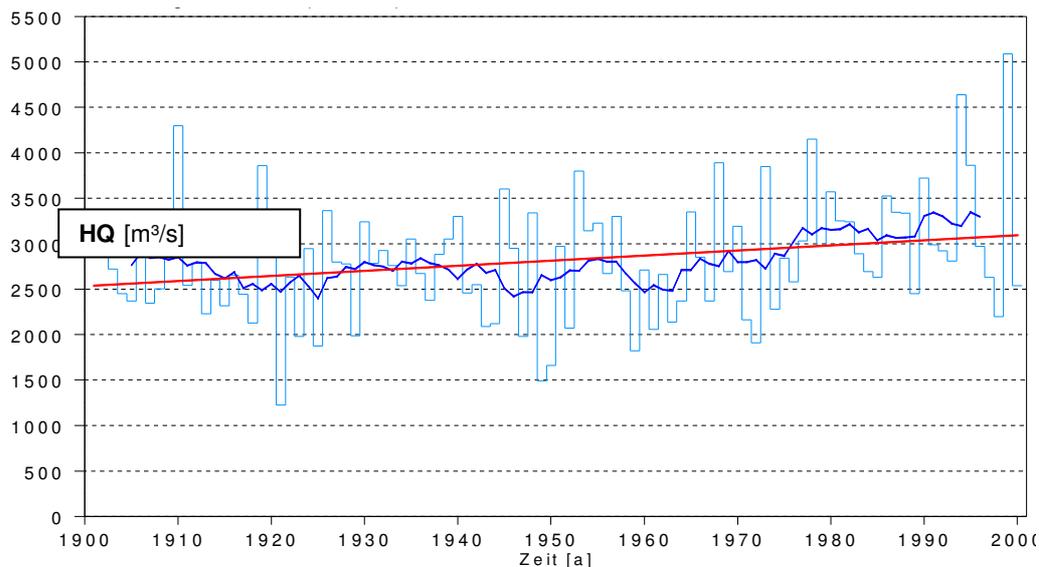
Fig. 15   Gauge Basel/Rhine – annual flood peak discharges (HQ), period 1901-2000
blue, bold: 9-year running average   red: trend (FQS)

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In addition to climate impacts, river engineering structures played a major role: in connection with the construction of the Grand Canal d'Alsace west of the Rhine following WW I and the canalisation of the Rhine up to the Iffezheim barrage (1977), dikes moved closer to the river for the sake of flood protection, thereby reducing flood plains from 220 to 90 km^2. Furthermore, the straightened river makes flood waves run off faster. As a result, they may be superimposed by waves from tributaries, especially from the Neckar river, under unfavourable conditions. This might cause an increase from 6000 to 6700 m^3/s in the peak discharge of 200-year-recurrence floods downstream of the mouth of the Neckar.

The dikes, however, are only designed for a maximum discharge of 6000 m^3/s. The Hochwasserstudienkommission für den Rhein (HSK) (Rhine Flood Study Commission) appointed to deal with this problem did not recommend to raise the dikes but rather to take a number of steps to reduce the flood peaks to the level prior to the river development.
1. In the event of floods, a part of the water volume usually discharged via the canalised sections, is rerouted into the natural Rhine river bed.
2. Construction of retention weirs in the river bed
3. Creation of polders

A retention volume of 290 million m^3 is required to restore flood protection for a 200-year-event. Provisions 1 and 2 are operational and may provide 82 million m^3 in the event of floods. The construction of polders is more time-consuming. The retention volume of the facilities finished to date amounts to 62 million m^3, leaving a total deficit of 146 million m^3. The measures implemented so far, however, are promising. According to model calculations, they allow the reduction of flood peaks in the Upper Rhine by approx. 30 cm in certain extreme cases. However, this effect is reduced to below 10 cm in the course of the river until reaching Cologne.

Extreme floods emerge in the Middle and Lower Rhine if sustained rainstorms, possibly combined with snowmelt, fall in the catchments of the tributaries in

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concurrence with a flood wave from the Upper Rhine. They have gained in intensity in the winter half-years in the course of the 20th century. In summer, by contrast, hardly any changes can be noticed.

The Moselle river is of special importance in this context. Given that low-permeability rocks with poor storage capacity prevail in the catchment, flood waves with a peak discharge of up to 4200 m³/s can evolve, thus by far exceeding the maxima of all other tributaries (cf: Aar river 2600 m³/s, Main at Würzburg 1200 m³/s).

The Lobith gauge on the Lower Rhine mirrors the overall development of the Rhine basin (Fig. 16). Almost consistently, floods occur in winter. It is clearly visible that the increase in flood peaks is primarily a consequence of a steep rise within the last three decades of the 20th century. Indeed, the decade from 1920 to 1930 also had a high flood rate, featuring the highest flood of the century (approx. 13000 m³/s in January of 1926).
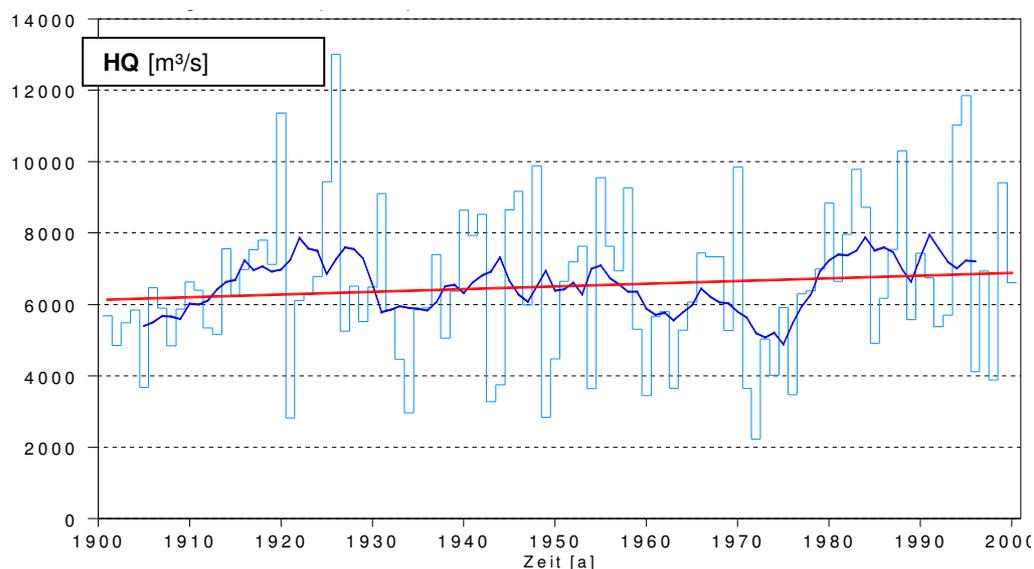
Fig. 16   Gauge Lobith/Rhine – Flood peak discharge (HQ) in the winter halfyears, period 1901-2000
                          blue, bold: 9-year running average   red: trend (FQS)

The actions taken to mitigate floods in the Upper Rhine also show their effects in the Lower Rhine. Even the first projects implemented give rise to expect reductions of several centimetres. A retention volume of 68 million m³ has been created by means of dike relocation to further minimise the risk. In the Netherlands, the programme "Room for the River" is intended to generate an additional area of 17 km² for overflow in order to reduce flood levels.

Low Flow
Although less spectacular than floods, periods of low flow are by no means less serious in terms of ecology and socio-economy, especially in view of obstructions to navigation, the lack of cooling water for thermal power stations, and diminished power production in hydroelectric plants. Unlike peaks of flood waves, there is no similarly distinctive low but an extensive depression curve. The lowest arithmetic mean discharge of 7 or 21 consecutive days (NM7Q and NM21Q) are used as

parameters for such extreme situations. Depending on the runoff regime, the typical low-flow period takes place in different seasons.
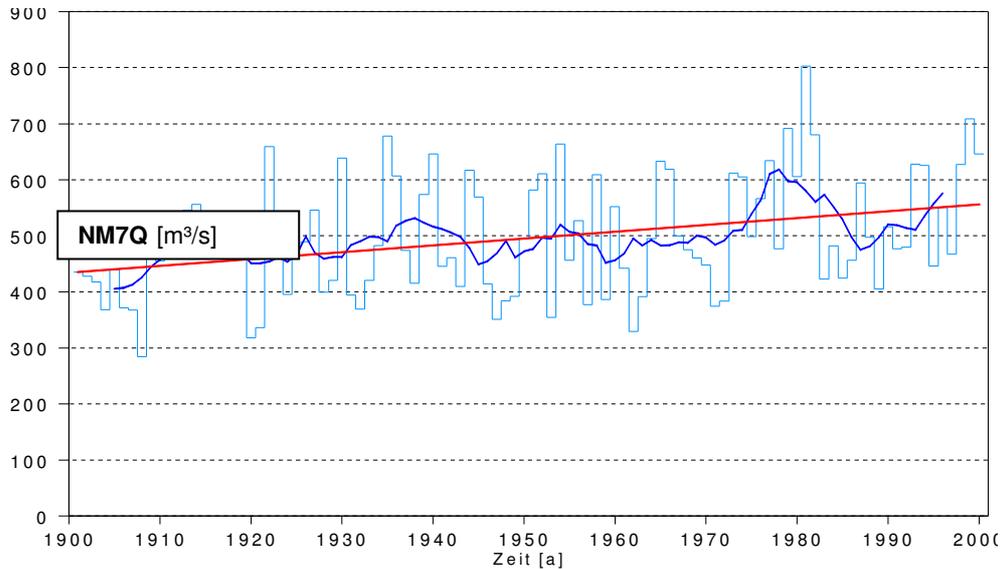
Fig 17: **Gauge Basel/Rhine – winter semiannual low flow extremes (as NM7Q), period 1901-2000**

blue, bold: 9-year running average **red: trend (FQS)**

Up to Basel, i.e. in the nival regime, it takes place in winter. Here, an attenuation of minimum flow can be observed (cf. Fig. 17). This is caused by the previously described redistribution of runoff from summer to winter due to a milder climate as well as an identical effect due to the management of reservoirs.
This trend continues into the Upper Rhine, the more so as winter low-flow periods on the Neckar and Main rivers are also attenuated owing to increased rainfall. Water transfers from Lake Constance or the Danube basin make themselves felt during extreme minimum flow periods in summer. At the Würzburg gauge, a rise in minimum flow from 35 to 48 m³/s is recorded.
Up to Cologne, minimum flow in winter has risen slightly, while no trend can be identified further upstream. Extremely low discharges below 700 m³/s (NM7Q) as observed until 1960, have no longer been recorded in the later part of the 20th century.

Summary

The present study is the first to document the development of a major river basin over an entire century and provide a quantitative-hydrological analysis. It was found that changes have occurred in the entire catchment, but they show spatial and seasonal differences.
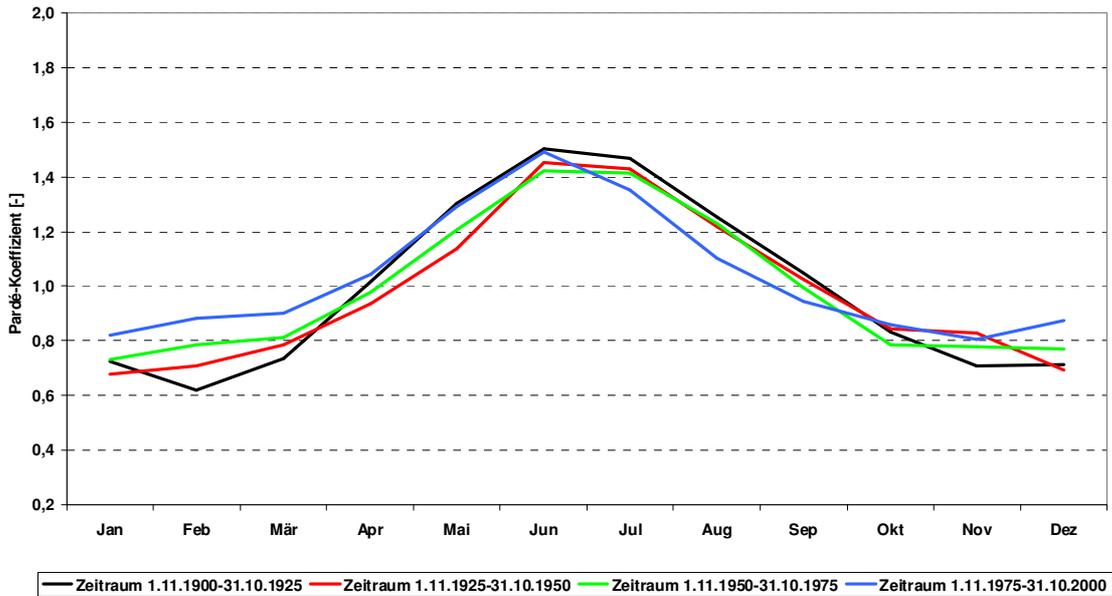
Fig. 18: Gauge Basel/Rhine – Development of the runoff regime (Pardé) in the 20th century using the annual run of the mean monthly discharges (mMQ)) in sections of 25 years, standardisation reference: period 1901-2000
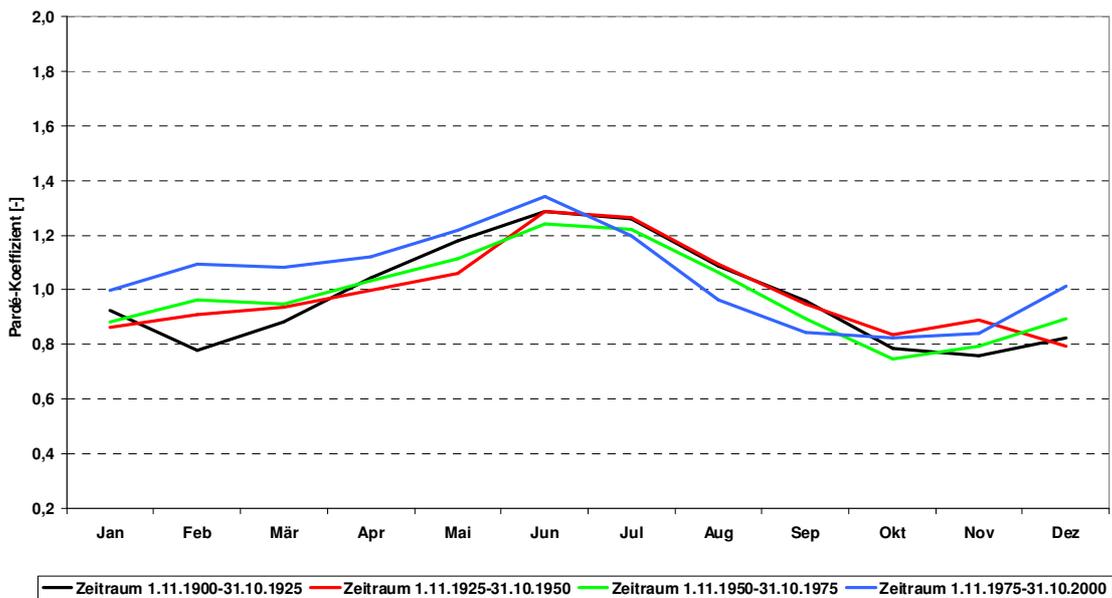
Fig. 19: Gauge Worms/Rhine – Development of the runoff regime (Pardé) in the 20th century using the annual run of the mean monthly discharges (mMQ) in sections of 25 years, standardisation reference: period 1901-2000

In the alpine and pre-alpine parts of the basin, runoff has shifted from the summer to the winter half year. Due to the temperature rise in the 20th century, more precipitation falls as rain than as snow in winter. Hence, there is no interim storage, but immediate runoff. Moreover, periods of thaw in winter cause premature snowmelt runoff resulting in a lack of snowmelt in early summer. Water transfer in-between seasons is reinforced by the identical effect exerted by reservoir management. The surplus of water stored in summer is released for power production in winter. Over the year, there is a marginal increase in runoff, as precipitations rise in winter.
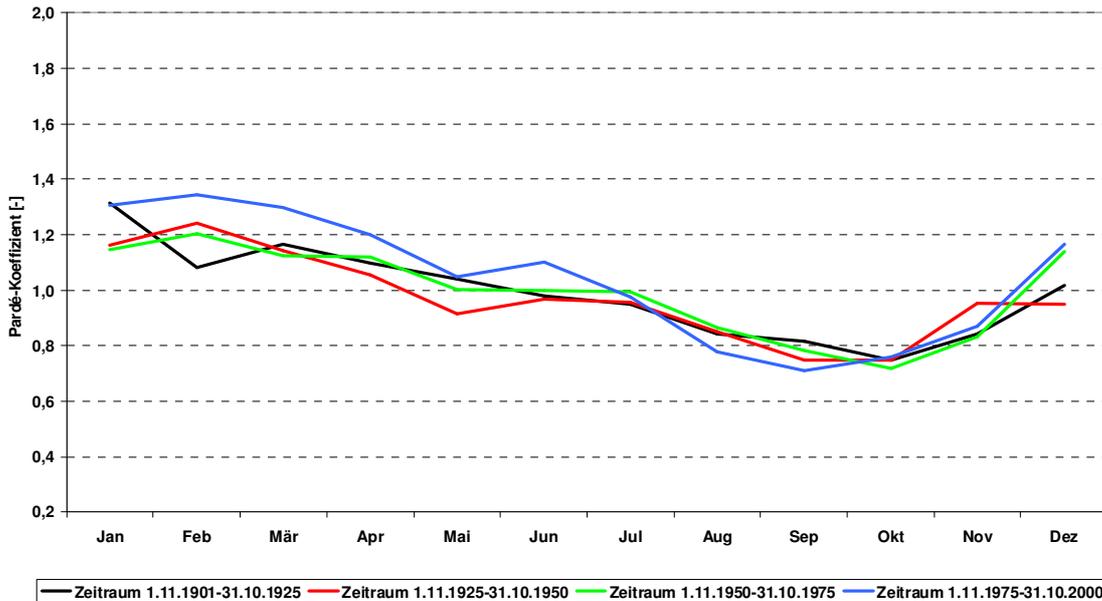
Fig. 20: **Gauge Lobith/Rhine – Development of the runoff regime (Pardé) in the 20th century using the annual run of the mean monthly discharges (mMQ) in sections of 25 years, standardisation reference: period 1901-2000**

In its further course, significant increases in the runoff of its tributaries prompt a rise in the Rhine's runoff. Owing to the precipitation development, the latter primarily happens in winter, to a lesser extent also in summer. Mean discharge at the Lobith gauge has increased by approx. 11% in the course of the 20th century. Flood peaks have risen in parallel. Low-flow extremes have been reduced mainly in the southern part of the Rhine basin, upstream of the confluence with the Main river.

The image can be further refined by looking at the runoff regimes at various Rhine gauging stations at an interval of 25 years. At the Basel gauge, runoff is more balanced owing to the contrary trend in summer and winter. This pattern continues into the Upper Rhine (Fig. 18), with the runoff peak in June remaining steady. Beginning at the Middle Rhine, particularly striking from the Andernach gauge onwards, the pluvial element becomes prevalent in the course of the century. Increasing winter precipitations in the catchments of the tributaries cause such increases in runoff in a season when the Rhine anyhow reaches its maximum monthly means. Thus, flood extremes, typically occurring in late winter and spring, are simultaneously on the increase in the pluvial regions of the catchments. On the other hand, minimum flows from August to September have hardly changed. This pattern continues as far as the Lobith gauge (Fig. 20).

The Rhine basin hosts a wealth of hydrological and meteorological data that is presumably unparalleled in the world. The challenge now is to preserve and maintain this treasure. It is not only a matter of collecting the greatest possible volume of data. In fact, much more attention should be devoted to data quality. Only flawless data with sufficient spatial and temporal representation allow well-founded scientific statements. Lacking this foundation, practical hydrology would have feet of clay – a condition that society cannot afford given the Rhine's significance.

Abbreviations used

FQS: widespread total least squares method (for trend analysis)

hm³: hector cubic metre (1 hm³ = 1000000 m³)

HQ: flood peak discharge, highest discharge within a reference period or period of time

MQ: mean discharge within a reference period or period of time

mMQ: mean monthly discharge

NM7Q: lowest arithmetic mean discharge of 7 consecutive days within a period of reference or a period of time

NQ: lowest discharge within a period of reference or a period of time

SumhN: Precipitation totals (SumhN) on monthly, semi-annual, annual and decadal basis;