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The flood events of 1993/1994 and 1995 in the Rhine River basin

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Abstract The causes of the Rhine floods of 1993/1994 and 1995 are described and compared with those of historic events. Information is given on damages and about consequences drawn at national and international levels.

GENERAL BACKGROUND

The flood events of 1993/1994 and 1995 and their underlying causes were media topics for weeks. Today, discussions continue as to why these floods were more frequent and their flood peaks higher. The main arguments are anthropogenic interference with nature.

GEOGRAPHICAL-HYDROLOGICAL OVERVIEW

In a comparison with the river basins of Amazonas or Mississippi–Missouri (7.2×106 km^2 and 3.2×106 km^2, respectively), the Rhine basin (Fig. 1) with its area of some 190 000 km^2 appears less spectacular. However, the Rhine is one of the rivers with the highest streamflow in Europe and has little seasonal variation in discharge. Moreover, the River Rhine is one of the busiest waterways in the world. Nine states share the Rhine basin and about 50 million people live there. With about 100 000 km^2, Germany has the greatest land area within the basin.

The 1320 km-long course of the river is divided into six major stretches: (a) the Alpine Rhine and (b) the High Rhine, which are influenced by more than 16 000 km^2 of high-mountain area, including about 400 km^2 covered by glaciers; (c) the Upper Rhine which flows through the lowland plain having a markedly flatter gradient than the High Rhine; (d) the Middle Rhine which breaks through the Rhenish Slate Mountains (Rheinisches Schiefergebirge) and whose meanders have cut 200 to 300 m down into the rock; (e) the Lower Rhine, which flows like a typical lowland river in wide meanders, splitting directly behind the German–Dutch border into several branches, forming (f) the "Rhine Delta". The important tributaries of the Rhine are the rivers Aare, Neckar, Main and Moselle.

The flow regime of the Rhine River is dominated by snowmelt and precipitation runoff from the Alps in summer months, and by precipitation runoff from the uplands in winter. Further downstream, the influence of the uplands grows more significant, and over the year the discharge becomes very even. The annual hydrographs of some gauges along the Rhine (Fig. 2) illustrate the changes in the flow regime along the river course and show that the discharge components from the

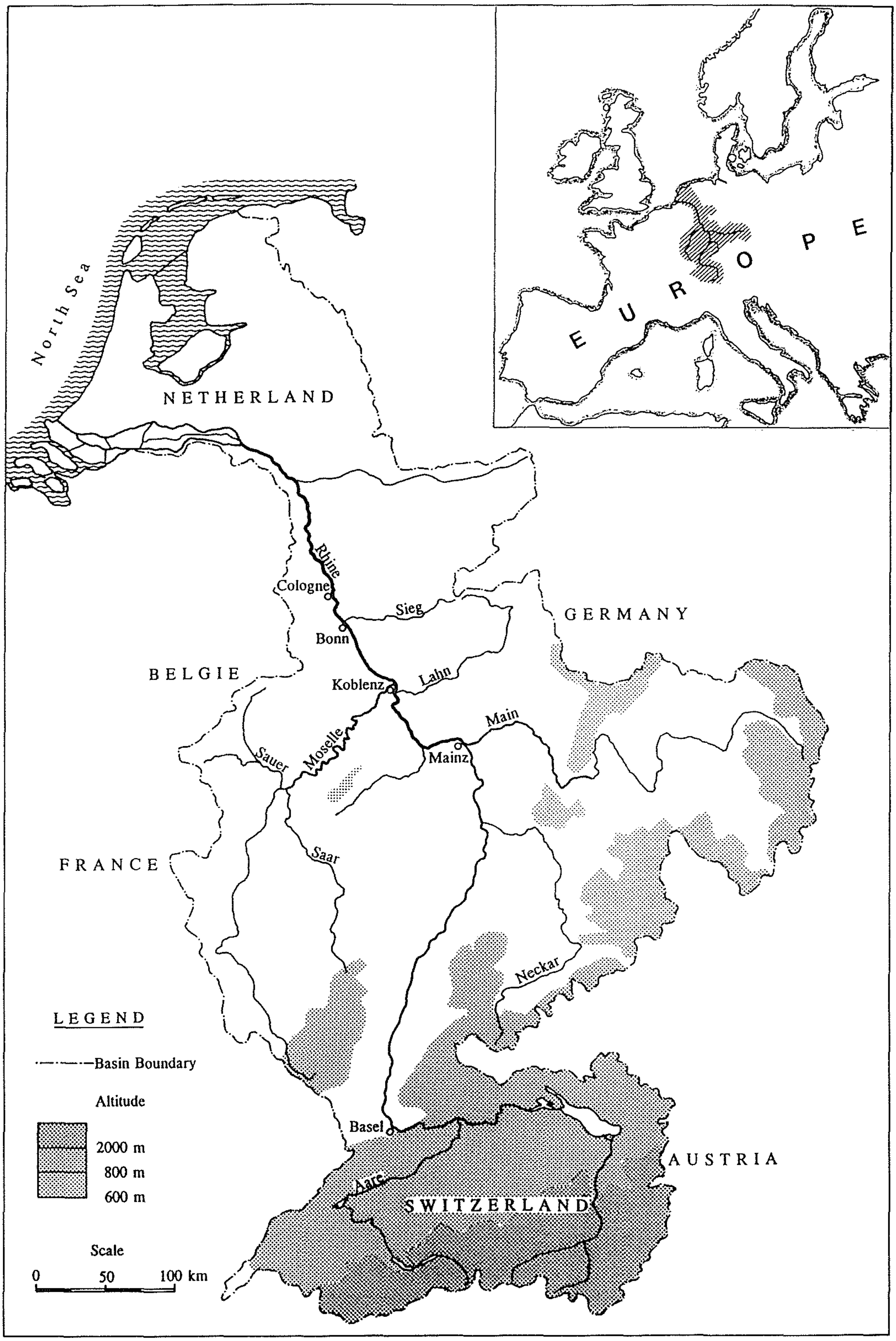

Fig. 1 Rhine River basin.

high mountains and those from the hilly country complement each other nearly ideally.

The Rhine River basin consists of a number of sub-basins which respond to very different meteorological conditions. Rhine floods have always become catastrophic when extreme runoff was discharged from several of these sub-basins at the same time. However, the long series of hydrological records (since 1000 AD) does not list a single flood event that has occurred simultaneously in all sub-basins with comparable magnitude.

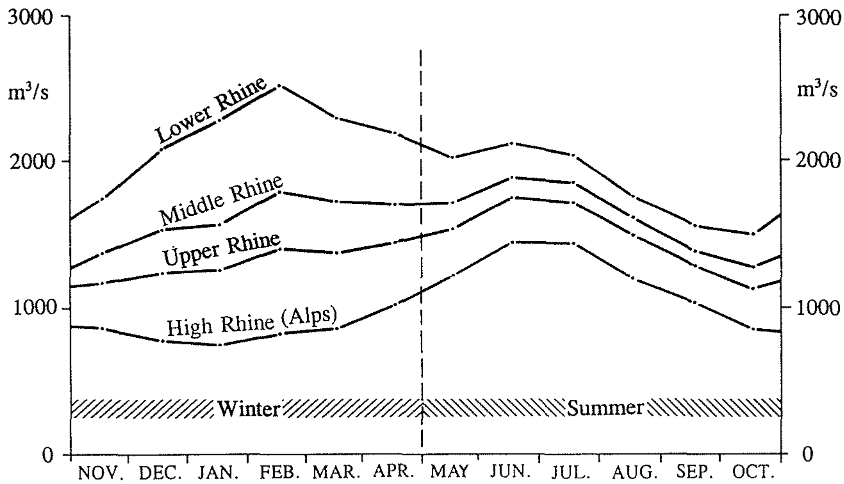

Fig. 2 Variation of mean monthly discharges at selected gauges on the River Rhine.

THE COURSE OF THE FLOODS OF 1993/1994 AND 1995

Neither the 1993/1994 flood nor that of 1995 had its origin in the Alps.

In **1993** (Engel *et al.*, 1994), a mean discharge situation at the border of the Alps developed on the Rhine reach to the mouth of the Neckar into a wave with a peak flow that recurs about once in two years. Simultaneously, the River Neckar began to swell to a 50-year peak. Only when the Rhine wave was further increased by the inflows from the River Main and Nahe did the recurrence probability of the peak flow in River Rhine jump to about 35 years. At Koblenz, the discharge peaks of the Rhine and Moselle met with little time lag. The flow in the lower Moselle, with nearly 4200 $m^3 s^{-1}$, the highest since the beginning of regular observations in 1817, generated a wave in the Lower Rhine with a peak that had been exceeded in this century only once. At Cologne, finally, it was so high and prolonged that the temporary flood protection wall, that had been erected there to protect the old city, was overspilled for about 70 h. The substantial dikes, that begin just a few kilometres north of Cologne, largely prevented flooding and damage further downstream.

In **1995** (Engel, 1995) the peak discharge at the border of the Alps corresponded to a recurrence period of about 20 years, but the flood situation there lasted only a short time. In the course of one day, discharges returned to the long-term mean high water.

Because the inflows along the Upper Rhine were rather insignificant, the recurrence interval of the peak in the River Rhine downstream to the mouth of the River Main fell below 10 years. However, with extreme flood flow in River Main, the maximum discharge in the Middle Rhine exceeded that of Christmas 1993. The situation was different at Koblenz, where the peak discharge of the River Moselle was more than 600 $m^3 s^{-1}$ less than in 1993, so that the water level remained 31 cm below that of 1993. Widespread extreme precipitation in the headwater region of a small tributary north of the mouth of the River Moselle increased the flood towards Cologne so much that—despite these favourable conditions upstream—the gauge there climbed 6 cm higher than in 1993, to reach the same level as the maximum water stage at Cologne in this century (in January 1926). The last gauging station before the German—Dutch border finally recorded 12 000 $m^3 s^{-1}$ and a stage 1 cm above the 1926 mark.

The two floods described were characterized by a very steep rise at the beginning. In the lower Moselle, for instance, the increase in water level of 5 m over 24 h meant a new record. Noteworthy is also the very great flow volume at the time of the inundation.

Figure 3 shows stereographic representations of the flood waves in the River Rhine of December 1993/January 1994 and of January 1995.

CAUSES OF THE FLOODS IN 1993/1994 AND 1995

A 10-day rain period in December 1993 in the flood source areas brought precipitation that equalled nearly 100% of the long-term December mean. Thus, the soil pore volume was practically filled and the land surface became impervious. In 1995, a similar effect was caused by melting snow and frozen soil in the higher uplands.

Precipitation during the actual flood periods was equivalent to 200% of the 30-year mean of December or January, respectively. The widespread "sealing" of the land surface and the distribution pattern of precipitation had the effect that in some areas in the northern Rhine basin 50–70% of the falling precipitation entered the water courses directly.

How extreme the situation was may be illustrated by the fact that of 50 precipitation stations 18 recorded the highest December precipitation of their 103-year observation series in December 1993. In seven cases it was the highest monthly precipitation ever recorded.

THE EVENTS OF 1993/1994 AND 1995 COMPARED WITH HISTORIC FLOODS

The media and public opinion denounce the frequency of extreme events and the height of the flood peaks of the River Rhine as manmade.

Here, one has to note the following: Floods are a product of widely distributed heavy precipitation falling on land surfaces with a high potential for surface runoff.

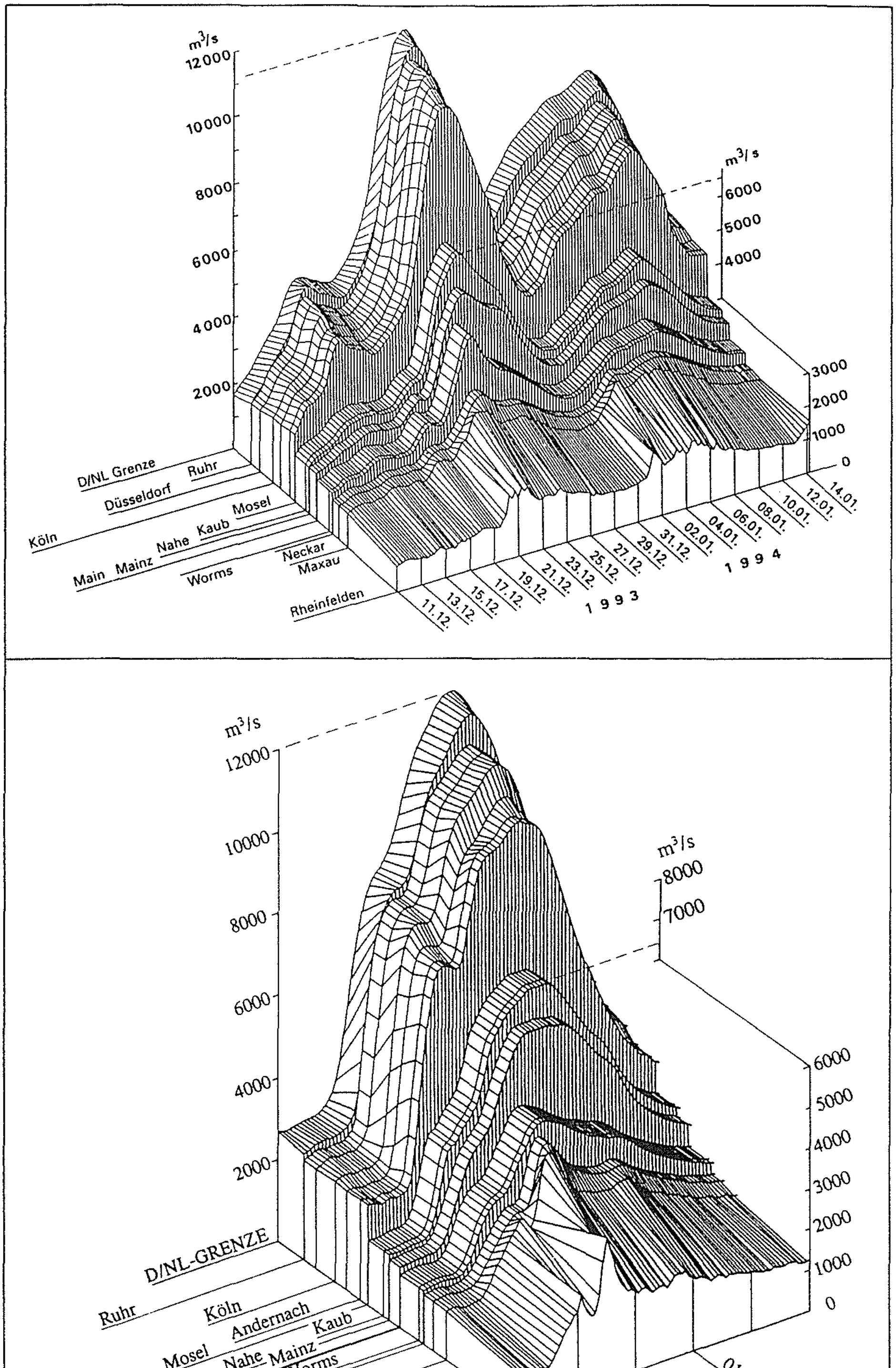

Fig. 3 Stereographic representation of the flood waves of December 1993/January 1994 and January 1995 on the River Rhine.

First of all, this means that only a small portion of precipitation can infiltrate into the ground, so that most of the water flows over the surface into receiving water courses. Locally, effects of urbanization such as paved surfaces can significantly intensify the formation of floods. On a large-scale, however, the portion of anthropogenically sealed land surfaces on German territory is only around 12%. Runoff coefficients of more than 50%, which are necessary to generate major floods, however, can be produced only by natural processes. With a view to the underlying causes of widespread extreme floods, no grave changes in recent times can be noted, as we can learn from reports and records on unusual hydrological events in the Rhine basin, collected and analysed from the year 1000 AD until today. The example of two floods from this era shall show us the essential causes for extreme river flow in former times as today (Engel, 1990).

In 1658 an extraordinarily extreme winter flood occurred. Chronicles report that the winter 1657/1658 had been very long and cold with excessive snow and floating ice.

The quotation "Severe frost was followed by thawing of incredible masses of snow and incessant rain ..." illustrates that the flood was produced by high precipitation and melting snow, which could not infiltrate into the ground because the soil was frozen.

A report about the year 1342 reads "In the same year there was great flooding in all waters, in winter just like in summer ...", "... and the floodgates of heaven were open, and rain pelted down onto Earth like in the 600th year of Noah's life, ..." Then, however, it continues: "This summer brought a great flood that was not produced by downpouring rain, it seemed that water gushed from everywhere, even from the tops of the mountains, ..." and "water was all over the land, although it had not rained much at that time ..."

It was reported that in the Mainz Cathedral the water "stood as high as to a man's belt". Since the beginning of regular gauge observations more than 170 years ago, the water of the River Rhine has never inundated this cathedral, although the river bed has not been eroded at this point.

The year 1342 is an example that floods used to occur occasionally twice in one year in the past, just like in 1970 and 1983. Moreover, the natural boundary conditions for a flood event with extreme antecedent wetness are described. First, the report mentions most abundant rainfall that is compared to the Deluge. Then it says that "water gushed from everywhere", i.e. that the ground was practically saturated with water. Finally, it is noted that the flood did not come from "downpouring rain", as "it had not rained much at that time". Once the soil is waterlogged, it does not need particularly intensive rainfall to produce flood flow as practically every drop of water falling to the ground flows immediately into the water courses. Similar weather situations produced the floods in 1993/1994 and 1995.

Statistical analyses of flood events usually consider only the peak discharges and the peak stages. A direct comparison of the flow of the flood wave and the consideration of the water volumes discharged in each case, however, can lead to new insights and occasionally reverse the assessments that were derived from the peak values alone.

Figure 4 shows the three major flood waves in the River Rhine at Cologne in this century with nearly coinciding peaks. The three events had nearly the same

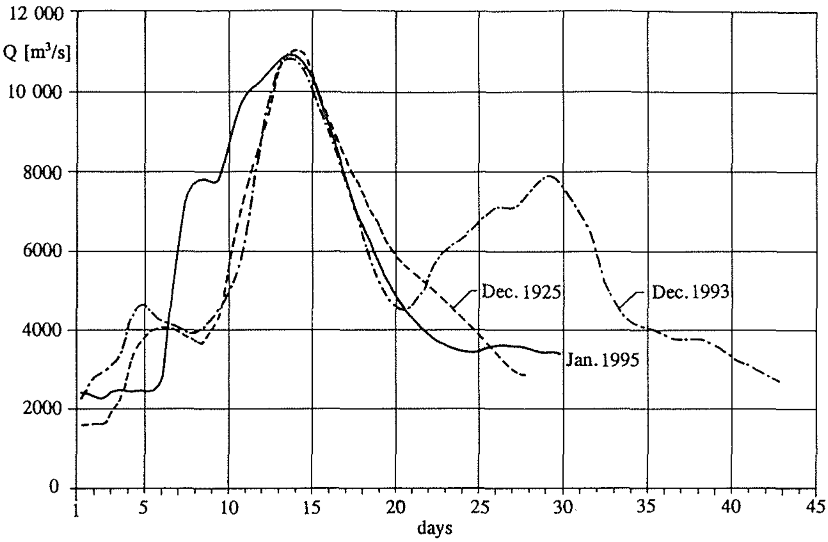

Fig. 4 Comparison of discharge hydrographs of the flood events 1925/1926, 1993/1994, and 1995 at the Cologne gauging station on the Rhine.

maximum water levels, and the waves of 1926 and 1993 were nearly identical in the shape of their hydrographs, while the wave of 1995 had a completely different shape and, above all, a considerably higher water volume. If one considers only the discharge volume above a water stage of 10 m at the gauging station Cologne (this is the volume of water that had to be retained in order to prevent overflowing of the temporary flood protection wall in front of the old city.) one finds for 1926 a volume of 194×10^6 m^3, for the 1993/1994 flood 167×10^6 m^3, and for 1995 even 270×10^6 m^3. It becomes clear, that retention capacities necessary for the protection of the riparian population depend on the water volumes above boundary stages. If the water volumes above the respective baseflow thresholds for the nine greatest floods since 1926 are compared, then the ranking is completely different than the one according to peak discharges as shown by Table 1.

Table 1 The nine highest peak discharges at the gauging station Cologne since 1926 and the water volumes of these waves above the respective baseflows.

Rank	Event	Q (m^3 s^{-1})	Volume ($\times 10^9$ m^3)	Rank
1	1925/1926	11 100	9.4	3
2	1995	11 000	8.0	4
3	1993/1994*	10 800	7.4	5
4	1947/1948	9 950	10.3	2
5	1983 (May)	9 910	3.5	8
6	1970	9 740	4.2	7
7	1983 (April)	9 690	4.2	7
8	1988	9 580	10.8	1
9	1955	9 550	6.9	6

* Only the main wave

NOTICEABLE GENERAL TRENDS IN DISCHARGE DEVELOPMENTS

The series of annual peak discharges of some Rhine gauging stations since 1891 show an increasing tendency (Engel, 1993). This applies to all the stretches of the Rhine, for instance also to the Lower Rhine at the Cologne gauge (Fig. 5). This development is alternating, occasionally interrupted by several years of recession. A comparison of annual low-flow discharges yields the same results as that of the flood-flow discharges, and even the mean annual discharges (*MQ*) have become higher.

On the whole, the increase in discharges is more marked further downstream.

From a long-term perspective, river discharge can only be understood as a response to the precipitation that has fallen in the catchment basin. Cumulative precipitation data for 40 stations in the Rhine basin downstream to Cologne were taken to be plotted as mean annual precipitation (Fig. 6). The selected stations are fairly evenly distributed over the Rhine basin and their observation series date back

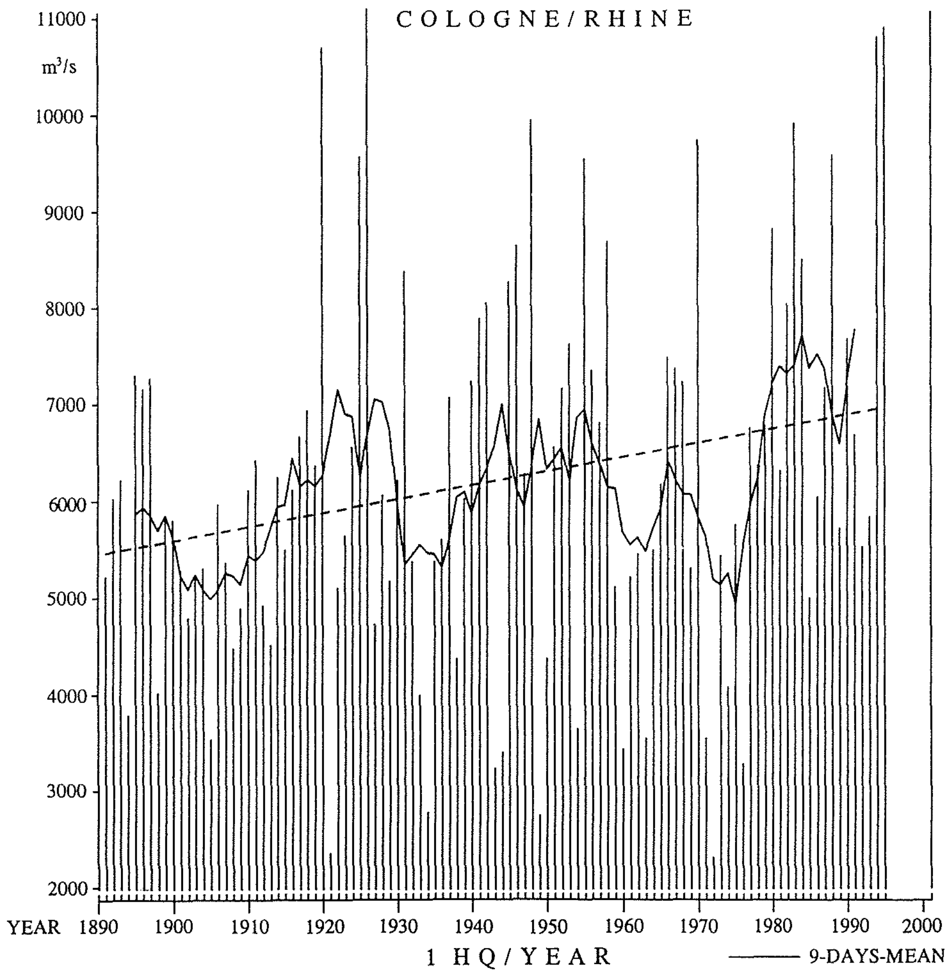

Fig. 5 High-water discharges (HQ) for the years from 1891 to 1995 at the Cologne gauging station on the Rhine.

at least to 1891. The tendency of precipitation parellels that of river discharge. To make this phenomenon better visible, the time series were smoothed by forming shifting averages over nine values each.

Climatologists have repeatedly pointed out that, as a consequence of large-scale increases of annual temperatures (in the Rhine area 0.6°C during 100 years), we have to expect, besides an increase in the cumulative annual precipitation, also a redistribution of precipitation. By contrasting the mean monthly precipitation of the two latest climatic periods (1931–1960 and 1961–1990) for the Rhine basin downstream to Cologne (Fig. 7), one finds that annual precipitation has increased there by more than 2.5%. Simultaneously, one notes a seasonal redistribution of precipitation, with decreases from June to October and over-proportional increases from February to May and in November and December.

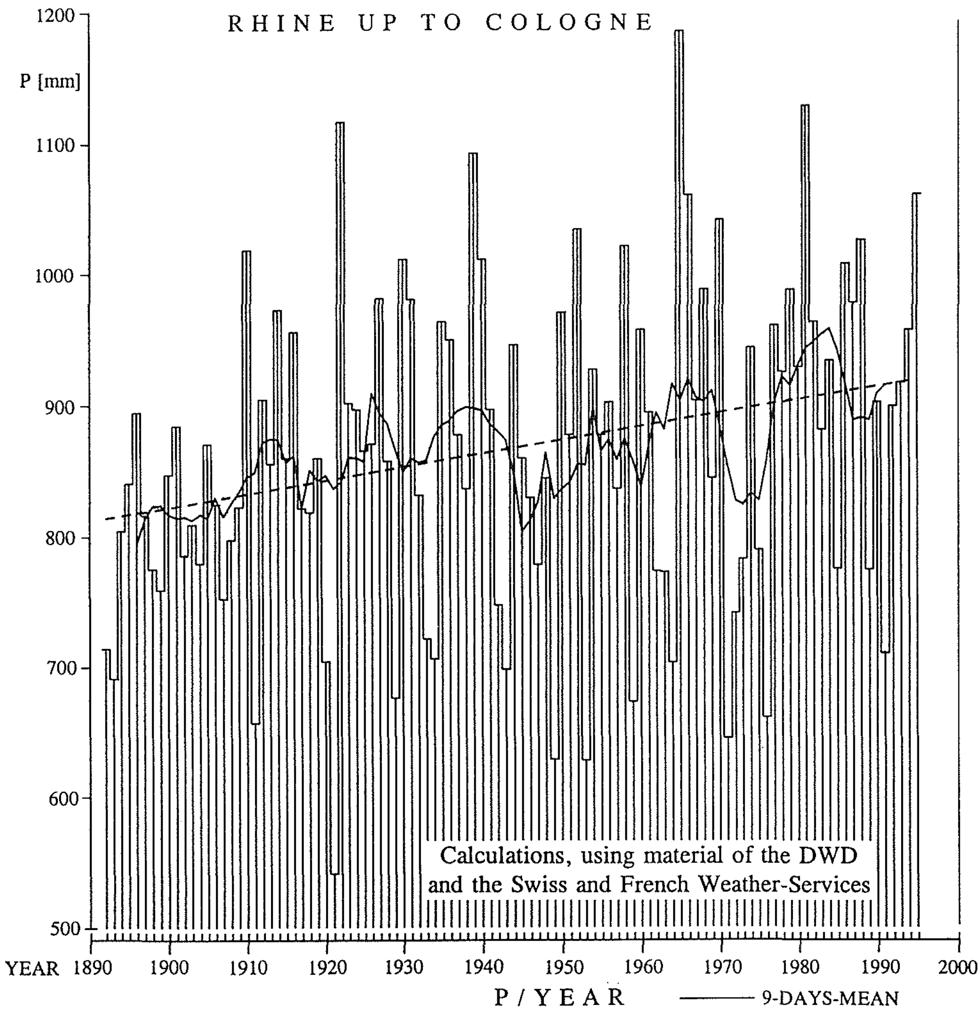

Fig. 6 Annual precipitation in the Rhine basin downstream from Cologne from 1891 to 1995.

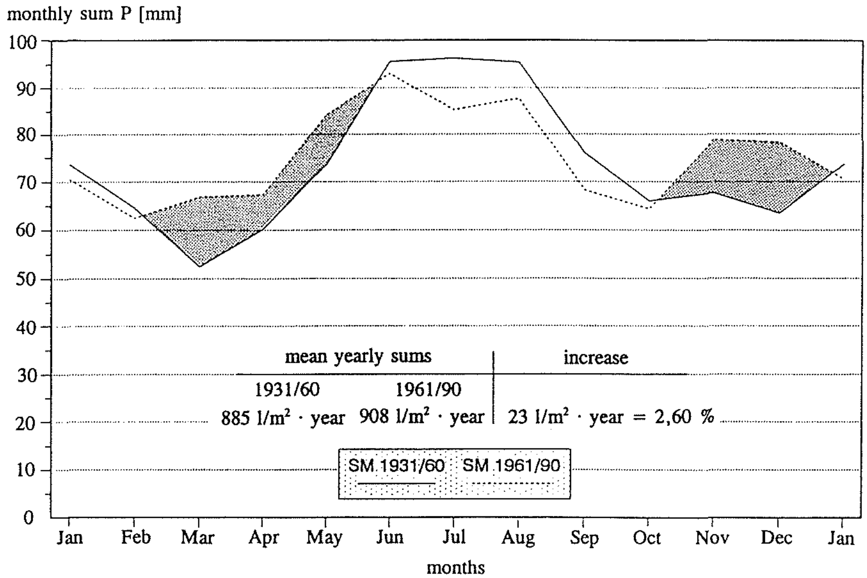

Fig. 7 Mean monthly cumulative precipitation (SM) for the periods 1931–1960 and 1961–1990 in the Rhine basin downstream from Cologne.

An analogous analysis of discharge tendencies in the River Rhine shows a strong increase in mean discharges in the months from March to May in the 100-year series, while the decrease in precipitation in summer months is reflected only in stagnating *MQ*s in the months from July to September.

Relating the redistribution of cumulative precipitation to the flood periods in the non-alpine Rhine area reveals that the increased precipitation falls just during the flood-prone months. So there is a suspicion that in future floods which develop due less to frozen or snow-covered ground but more to prolonged antecedent rain, may become more frequent—with a likely concentration around the end of winter or in early summer, respectively.

THE IMPACTS OF THE FLOODS

The population living along the Rhine is protected by dikes, apart from a reach of 180 km, which provide safety for events of 200 to far beyond a 1000-year recurrence interval.

None of the tributaries of River Rhine has protective dikes over longer reaches. Some settlements have protective structures which vary considerably in height. This means that the overwhelming number of riparian dwellers on the Rhine tributaries have to live with floods and have developed strategies to cope with rising water stages. This applies also to the inhabitants of the Middle Rhine valley. Damage through flooding remain usually limited here. However, it was different during the flood 1993/1994 because of the unusual height of the flood peaks and the rapidity of the rising waves.

Nowhere in the Rhine basin were protective dams destroyed. The water stages remained far below the critical levels. However, on the Lower Rhine widespread inundation occurred behind the dikes through seepage and suffusion.

Protective walls, that had been erected in front of settlements, were not destroyed, but they were not substantial enough to cope with the highest floods so that they were overtopped in some cases (e.g. at Cologne).

The damage of the events 1993/1994 in the whole German basin of the River Rhine was estimated at DM 1.5 billion. The sum that was established for 1995 amounted to some DM 500 million. It is noteworthy here that the damages inflicted in 1995 were less although the flood situation of 1993 and 1995 were comparable and water stages in 1995 in Cologne and downstream had sometimes been higher than in 1993. The explanation for this phenomenon lies in the fact that in 1995 the warnings and forecasts received more attention and were taken much more seriously. Many of those affected had cleared their houses even beyond the water level of 1993. This preceding flood was obviously still fresh in everybody's memory, and people had learnt their lesson. Obviously, the closer relation between the subjective expectations for the extent of the flood and the objective threats helped to reduce damage.

NATIONAL AND INTERNATIONAL ACTIVITIES FOLLOWING THE FLOODS OF 1993/1994 AND 1995

Over the past few decades extreme floods have repeatedly affected the Rhine basin and other regions in Germany. The echo in the media was always loud but only of short duration. Not so after the flood at Christmas 1993. Discussion about the causes of the 1993 event in particular and about great floods in general were still going on in 1995 all over Germany and new fuel was added to the fire when the January flood occurred. Even 18 months later the interest in the problem of floods is still vivid. It is pleasing and satisfactory to note that in the meantime some better understanding has been developed in the media, among politicians, and in the local population. Last not least extensive educational work has contributed, and the damage suffered has also furthered insight.

Already after a major flood in the year 1988, along the German reach of the River Rhine a number of communities and citizen interest groups had initiated measures dealing with floods. The content of many statements consisted mainly of demands addressed to upstream dwellers, politicians, to those allegedly or actually responsible; but also self-criticism was voiced and even contributions to improve the situation were offered.

By now extensive programmes are underway to increase the retention capacities on River Rhine (construction of polders, renaturation of water courses) and to improve the dike systems deemed necessary. Measures have been taken to create retention capacities in the subcatchments, the renaturation of small waters is encouraged, and possibilities for storing precipitation water in the soil are recommended. Incentives are given to render paved surfaces pervious again and tests are made with intentional seepage in drainage systems.

In many regions authorities have begun to redefine the limits of inundation areas which had been last reviewed in 1913. In parallel, new ordinances on flood-related issues are being formulated. In late 1995, the outcome of a joint study of representatives of the Federal authorities and those of the *Länder* on River Rhine for determination of the potential flood damage on the Upper and Middle Rhine was published. This study is also a contribution to increase the general awareness about the risks of floods.

Another impetus for increased "flood consciousness" are the *Guidelines for Future-oriented Flood Protection* compiled by the German *Länder* Water Working Group (LAWA) for the Conference of Environmental Ministers in 1995. The findings are summarized in 10 guidelines, and it is noteworthy that five of these guidelines are addressed to those affected—calling for their action and understanding.

Still under the impression of the extreme floods of 1993 and 1995, the Environmental Ministers of the EU (in consultations with Switzerland) adopted on 4 February 1995 the "Declaration of Arles", which ordered the International Commission for the Protection of the Rhine (ICPR) to develop an "Action Plan for Floods" for River Rhine and its tributaries. Since then working parties draft presentations of existing flood risks, flood protection measures, initiated programmes, and joint strategies for the future, have been produced.

An important field of international activities is seen in the further development of legislation on water resources, soil protection, and regional planning. Finally, the Premiers of the *Länder* decided at a conference in March 1995 to take up negotiations with the insurance industry about possibilities for insurance against flood damages and also to examine the feasibility of a fund, from which private precautionary measures for prevention or mitigation of flood damages could be supported.

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