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3.1.5 Changing river discharges

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SUMMARY: *This section presents in its first part the development of the river discharge rates of the large German rivers Rhine, Weser, Elbe and Danube. The mean discharges of all these rivers show a positive trend during the past decades, with a particular significant increase for the river Rhine since the 1970ths. An increase of annual maximum discharge values is most significant in case Rhine after 1960, and less significant for the Danube, while the Elbe and Weser show no particular trend. Concerning trends of the low flow values, the Rhine – and to a lesser degree also the other rivers – show a positive trend, which can mainly be attributed to the low flow management in summer by using reservoirs in the mountain parts of the rivers. The second part of this section introduces the effects of land use on the development of river floods. It is shown, that land use influences flood production the strongest (up to 20% runoff increase), if rainfall intensities are high and antecedent soil moisture is low. This situation can occur for summer convective rainstorms. However, summer rainstorms are local meteorological phenomena which do not trigger wide-spread floods in large river systems, but only in small catchments. Large river floods are caused by advective, long lasting rainfall, which do hardly cause runoff processes influenced by land-use changes.*

The term »discharge« (synonyms: flow rate, streamflow) is used in this report as the water volume that flows through a certain cross-section during a unit of time and can be attributed to a catchment area.

Discharge is permanently varying, so that such changes are responses to the given natural conditions (soil conditions, antecedent and present weather conditions etc.). However, these changes are not the topic of this paper since they are only variations which superpose themselves over the mean-term and long-term tendencies and trends. In order to make the mean flow behaviour visible it is necessary to eliminate the superposing influences.

Streamflow variations of major German Rivers

The rivers Rhine, Weser, Elbe, and Danube (*Fig. 3.1.5-1*) were selected here for the description of the streamflow situation, although they were examined only at the at the gauging stations.

Streamflow measurements with an accuracy that is comparable with that of today's methods became possible with the development of the propeller-type flow-meter (in 1790). However, it took until the end of the 19th century to make this method common practice and to have regular flow measurements allowing to establish reliable stage/discharge relations. This explains why only since around 1890 reliable streamflow data have been derived from water-level measurements that had been recorded over decades before.

The anthropogenic influence on streamflow begins already at the springs and the headwaters and ends only when the rivers discharge into the sea.

These interventions aim to ensure that water resources are still available when the natural supply ceases and that floods are diverted or retained whenever possible in order to provide protection against inundation. However, if the hardly quantifiable anthropogenic influences on climate are left out of account, the mean streamflow behaviour (at least of larger watercourses) is dominated by natural processes.

Fig. 3.1.5-2 shows the annual mean discharges (MQ) at selected river gauges in the time series 1891–2002. One finds in all these rivers tendencies towards higher discharges. These increases were particularly striking in the 1970s in the River Rhine downstream with the course of the river. The gauges on the River Rhine recorded between 1940 and 1960 a period of reduced flow, as it had occurred in the lower Weser River between 1920 and 1950, while no such low-flow period was observed in the rivers Elbe and Danube.

The statistical analysis of the long-term pattern of mean river discharges in Baden-Württemberg and Bava-

Fig. 3.1.5-1: Basins for the most important rivers in Germany: Danube, Elbe, Odra, Rhine and Weser.

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ria (KLIWA 2003) on the basis of the data from 160 gauges revealed that the majority of the examined trends did not show any significance. Moreover, the intensity of the trends is low at most gauges and the deviations are both positive and negative.

Floods (HQ) in inland waters are usually the consequence of extraordinarily intensive rainfalls, and just like those, they are usually more or less short-term and often local events. Anthropogenic influences on floods are diverse and have existed for centuries. These are actions or measures affecting the catchments, changing soils, land cover, settlements, and – of course – also the watercourses directly. Dyking, rectification, and modification of river profiles have changed the temporal advance of single flood waves and the coincidence of tributary waves in river systems. This often results in faster, steeper, and higher waves than before. The actual flood event is ultimately a hardly distinguishable combination of weather-induced, climatic, and anthropogenic components that mix in different ways according to the spatial and temporal genesis of the flood.

The annual flood peaks since 1891 (*Fig. 3.1.5-3*) show generally significantly rising trends along the German reach of the Rhine, with some periods that are contributing less to this trend or even show a reverse development. Extraordinary streamflow was recorded in the 35 years from 1890 to 1925 and in the time from 1960 until today. Lower tendencies of rise dominated the River Danube, while flood events in the River Weser and in the upper Elbe decreased in the period under review. Floodflow in the River Elbe is obviously free of any trend.

With view to observed and expected climate changes and their impacts on floods, there are sometimes considerable differences between large-scale and micro-scale phenomena. In response to the findings of the KLIWA studies in southern Germany, the Federal States of Bavaria and Baden-Württemberg introduced a factor »Climate Change« into their hydraulic engineering guidelines. Bavaria increased the design flood (BHQ) generally by 15% for new construction projects. Baden-Württemberg recommends increases of design parameters between 0 and 25% on the basis of region-specific studies.

In contrast to floods, low-flow events are no short-term events but consequences of antecedent developments usually over several months. Anthropogenic influences result from water uses along the river course (extraction of drinking water and process water) and from medium-term retention in reservoirs in the catchments or in impoundments within the watercourses themselves. Consequences are, on the one hand, flow-reducing water losses and, on the other hand, flow-supporting water-releases from these reservoirs. Massive releases of stored water may even reverse the natural trend of decreasing low-flows.

Time series of the lowest annual discharges *(Fig. 3.1.5-4)* in the River Rhine show generally increases (just like MQ and HQ) with the particular gradients in the periods from 1890 to 1935 and from 1960 to date that were observed with other primary values as well. In the interval from 1935 to 1960, low flow (NQ) showed a slightly falling tendency. The flow behaviour in the River Weser was more constant, generally also with a rising tendency but with an emerging NQ decrease in the downstream reach over the past 35 years. The situation of the River Elbe is similar to that of the Weser. The River Danube shows between Regensburg and Passau weak increases in flow with a generally very even curve. However, downstream of the inflow of the River Inn, the Danube has a similar flow pattern like the Rhine. This may be an expression of the influence of the Alps, which have similar effects in the rivers Rhine and Danube, where the water storage in the mountains compensates the low flow (NQ). A Swiss study (Birsan et al. 2004) noted »that the natural runoff regime in Switzerland has notably changed since 1961«, namely due to »increase of the annual flow, .. particularly the winter maximum discharges (at about 60 ... 70% of the considered gauging stations) and the moderate to low discharges in the spring season«. Special reference is made to a »marked increase of ... days when the minimum temperature is above the 0° C threshold«. Thus, the conclusion seems to be justified that »with view to changes in the runoff regime, alpine catchments show the most sensitive response«.

Here it seems appropriate to mention the contribution of glaciers to runoff. Again and again, one finds references to the significant contribution of glacier meltwater to support streamflow in summer in catchments with alpine influence. This leads to the concern that receding glaciers (deglaciation) or ultimately the disappearance of glaciers would dramatically reduce summer streamflow in these rivers. As to the Alps, one should keep in mind that even in the high-mountain headwaters the share of glacier-covered area is very marginal (e.g. in the Vorderrhein basin at the gauge of Ilanz: Area = 776 km², glaciation 2.7%). Accordingly low is the contribution of meltwater to the total runoff [e.g. at the gauge Ilanz around 1% (BWG 2005)]. This applies particularly to the River Rhine or the River Danube further downstream. In 2003, in a year of extreme low-flow, streamflow in the Rhine at Cologne (with an Area of 145,000 km²) was in the monthly average of September 791 m^3/s. The associated cumulative discharge from glacier-dominated alpine tributaries reached 23 m^3/s, i.e. 2.9% of the MQ at Cologne drained from an area of 968 km², what corresponds to 0.7 of the Rhine's Area. The portion originating from glaciers in the sub-basins of about 3% reaches merely 0.02% of the Area at Cologne.

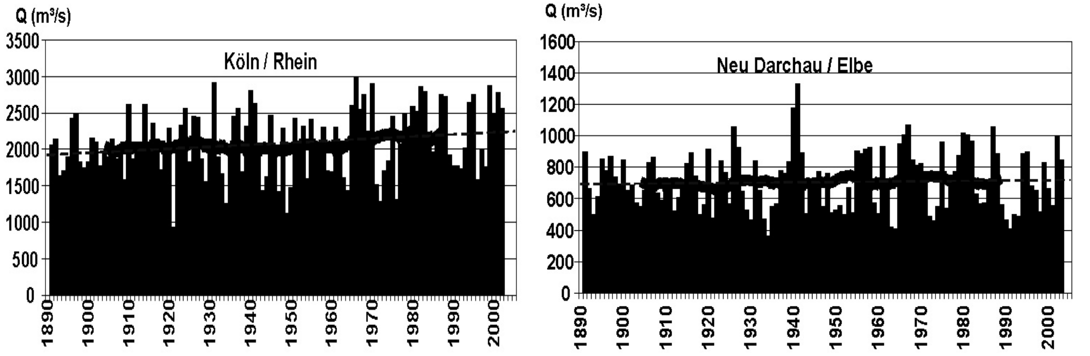

Fig. 3.1.5-2: Mean discharges (MQ) with trend curves and 30-year shifting averages at selected gauges on the German rivers Elbe and Rhine (time series 1891–2002).

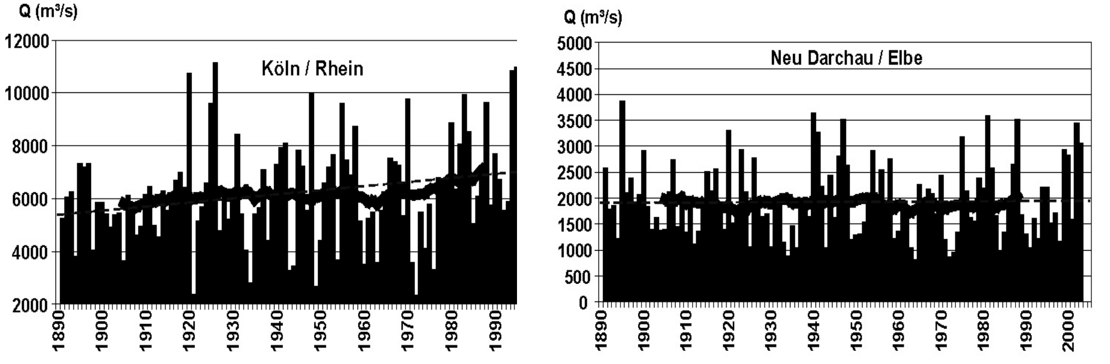

Fig. 3.1.5-3: Maximum discharges (HQ) with trend curves and 30-year shifting averages at selected gauges on the German rivers Elbe and Rhine (time series 1891–2002).

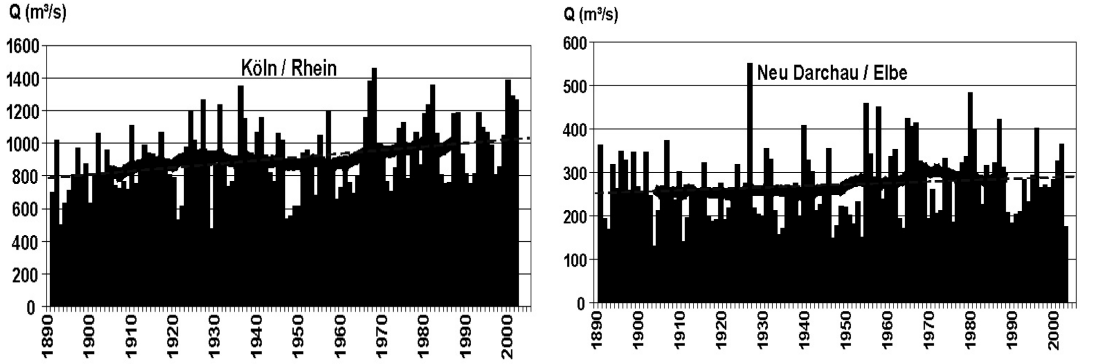

Fig. 3.1.5-4: Lowest discharges (NQ) with trend curves and 30-year shifting averages at selected gauges on the German rivers Elbe and Rhine (time series 1891–2002).

Accordingly, the influence of glaciers on the hydrological conditions of the Lower Rhine (as well as on the Danube downstream of the Alpine region) is negligibly small, even in years of hydrological drought.

The extreme events that have occurred in the past few years in the watercourses of Central Europe gave rise to the impression that they are consequences of trend-dominated developments. This was also the case in the extreme drought year of 2003. It gave the inspiration for an analysis of low-flow developments in Germany (BELZ et al. 2004), which found throughout the time series 1944–2003 increases in NQ. This means that despite this recent event, a general reduction of the risk of low-flow conditions can be substantiated, partly even as significant trend (*Table 3.1.5-1*).

As far as these developments concern the mean streamflow values, they are obviously related with climate. Trends towards increased mean temperatures in winter and annual precipitation let expect increases in mean streamflow also in the future. However, the developments of the extremes are less obvious, they do not occur uniformly, and are difficult to interpret. Anthropogenic interventions in waters and catchments that resulted in the past often in an acceleration of the flood-waves will probably be avoided in the future. Instead, flood-retention facilities will be used with the aim to alleviate extremes, but also to slow down flood waves. Climate-induced adverse effects, however, probably cannot be fully compensated.

For the Rhine basin, runoff developments were predicted with climate models for different target scenarios (CHR 1997). For example, hydrographs of mean annual discharge at gauging stations were computed (*Fig. 3.1.5-5*) according to the assumptions of scenarios of advancing climate change for the year 2100. Accordingly, at Rheinfelden (alpine regime) a shift of the mean annual maximum from June to April has to be expected together with a reduction of the discharge peak (CHR 1997). At Lobith (Lower Rhine), the time of occurrence of the peak will remain the same, but its height will rise by about 20%. The threatening message is in the first part of this statement, although it sounds rather harmless. In fact, it means a considerable deterioration of the flood-situation. The reason behind is the fact that the floods in the Alpine Rhine and the High Rhine that used to be restricted to the summer months may occur already in April as a consequence of global warming and may superimpose with the floods originating from the mid uplands. Such a constellation has never been mentioned in the historical records from the past 1,000 years (KHR 1995). Floods that emerge already at the foothills of the Alps as extreme events and are then steadily filled up on the downstream course of the river may reach dramatically heightened, unprecedented peaks in the Lower Rhine.

Table 3.1.5-1: Trend analysis on the basis of the Mann-Kendall test and the t-test (α = 5 %) of low flows, period 1944–2003.

Station	***Parameter***	***Tendency rising + falling –***	***Significance***	
			Mann-Kendall	***t-Test***
Hofkirchen (Donau)	NM7Q NM21Q	+ +	no no	yes yes
Maxau (Rhein)	NM7Q NM21Q	+ +	yes yes	yes yes
Köln (Rhein)	NM7Q NM21Q	+ +	no yes	yes yes
Dresden (Elbe)	NM7Q NM21Q	+ +	no yes	yes yes
Neu Darchau (Elbe)	NM7Q NM21Q	+ +	no no	no no
Hohensaaten-Finow (Oder)	NM7Q NM21Q	+ +	no no	no no
Intschede (Weser)	NM7Q NM21Q	+ +	no no	no no

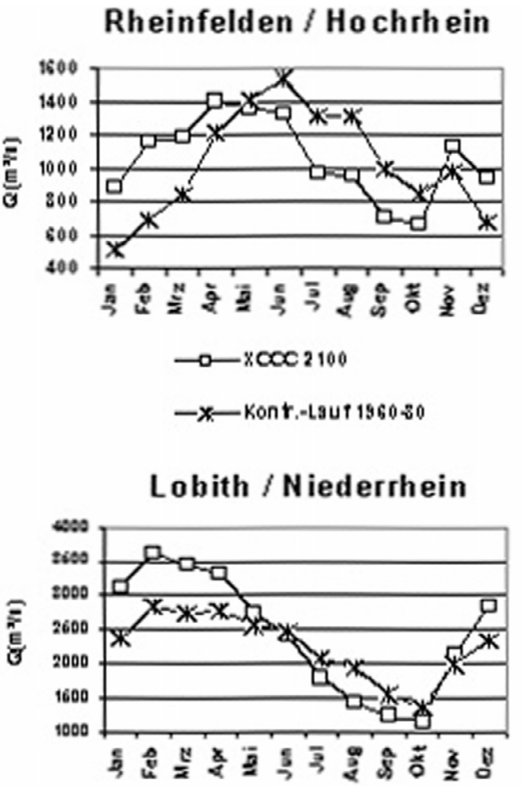

Fig. 3.1.5-5: Mean monthly discharges at the Rhine-gauges Rheinfelden and Lobith predicted by a climate model for the year 2100 in comparison with the mean discharges in 1960/80.

The influence of changing land use in the catchment on flood discharge

There are general indications that changes in land use in the catchments have consequences for the flood situations of the rivers. In discussions of the general public, extreme floodflows or even the resulting severe damage are directly ascribed to man's activities. The »natural« flood-proneness of a landscape is then often pushed into the background. The generation, progress, and damage of floods are sometimes insufficiently differentiated, and the cause-effect relations are not fully understood.

A fundamental problem in the quantification of anthropogenic impacts is their still high uncertainty. This applies particularly to possible variations in precipitation due to climate change and to the influence of changing land use on flood-runoff generation. The following chapter summarises the present state-of-the-art, and recent modelling outputs are used to compare and discuss the anthropogenic impacts with the natural conditions that govern runoff generation. We explicitly note that both climate change and the modification of the geometry and roughness of the river cross section may also contribute to changes in floodflow behaviour, although such anthropogenic interventions are not the topic in this paper.

The significance of runoff generation and of the water-storage capacity of the landscape during heavy precipitation

In analysing and modelling runoff-generation processes, the underlying spatial and temporal scales have high significance. The designation of the different spatial scales in this paper follows the classification by Dooge (1986) in local scale, hillslope (reach) scale, and catchment scale. The most important processes of runoff generation during heavy-precipitation periods are infiltration-excess overland flow, return flow, subsurface stormflow, and groundwater runoff. These different processes of runoff generation have different relevance on the above-mentioned scales.

The local scale is particularly suitable for studies and observations of the infiltration capacity of the soil; this means the infiltration capacity of the top soil that is determined by soil type, the actual soil moisture, and the presence of coarse (or macro-) pores. If the precipitation intensity is higher than the actual infiltration capacity, the excess water is drained in form of the so-called infiltration-excess overland flow. The infiltration capacity of the soil surface may increase by several orders of magnitude through the presence of macro-pores (mostly root ducts, tunnels of burrowing animals, or contraction fissures). Conversely, siltation or crusting of the soil surface may considerably lower the infiltration capacity and thus intensify the water excess for overland flow.

The hillslope scale is preferentially used to describe the lateral processes of runoff generation. One of them is subsurface stormflow that may occur during heavy rainfall in combination with high infiltration rates and anisotropic conductivities (shortcuts) in hillslopes. On average it does not occur frequently, but it has relevance for flood generation in mountainous areas, where the above-mentioned preconditions (high infiltration of rainfall, shallow and anisotropic soils) prevail.

A frequent process of runoff generation is the so-called saturation-excess overland flow that occurs on saturated soil areas because of the lacking ability of the soil to take-in water, which then rapidly flows into the receiving waters (streams). The amount of the saturation excess depends on the extension of saturated soil areas and on their connection with the receiving drainage system. Generally, it can be said that saturated soil areas expand with rising mean areal soil moisture. Their expansion depends mainly on the topography and the morphology of the area (thickness and porosity of soil layers, depth of the groundwater table).

Groundwater, too, may contribute significantly to the generation of floods, although its response time to heavy rainfall is longer than that of surface runoff. Mostly, groundwater exfiltrates directly from the aquifer into the stream. A relatively rapid exfiltration of groundwater, that can thus contribute to flood generation, is caused by a short-term intensification of the hydraulic gradient in the aquifer.

One can summarise that the runoff generation from heavy precipitation consists of several sub-processes, wherein the infiltration capacity (= the condition of the soil surface) is relevant only for the formation of the infiltration-excess overland flow. The occurrence of the other processes mentioned (saturation-excess overland flow, subsurface stormflow, exfiltration of groundwater) is dominated by flow processes in the underground, while the duration and amount of rainfall is of high importance for all the processes mentioned above.

The rainfall intensity has additional significance for the amount of overland flow, because it depends on the balance between rainfall intensity and the actual infiltration capacity of the soil surface. *Fig. 3.1.5-6* gives an overview of the processes of runoff generation on the hillslope scale.

The temporal dynamics and the extent of runoff generation is moreover dependent on the water-storage capacity of the landscape. Key functions of this storage in the context of flood generation are (1) the maximum storage volume, (2) the velocities of storage filling and draining, (3) the degree of filling at the beginning of the event. The degree of the effective influences on the flood

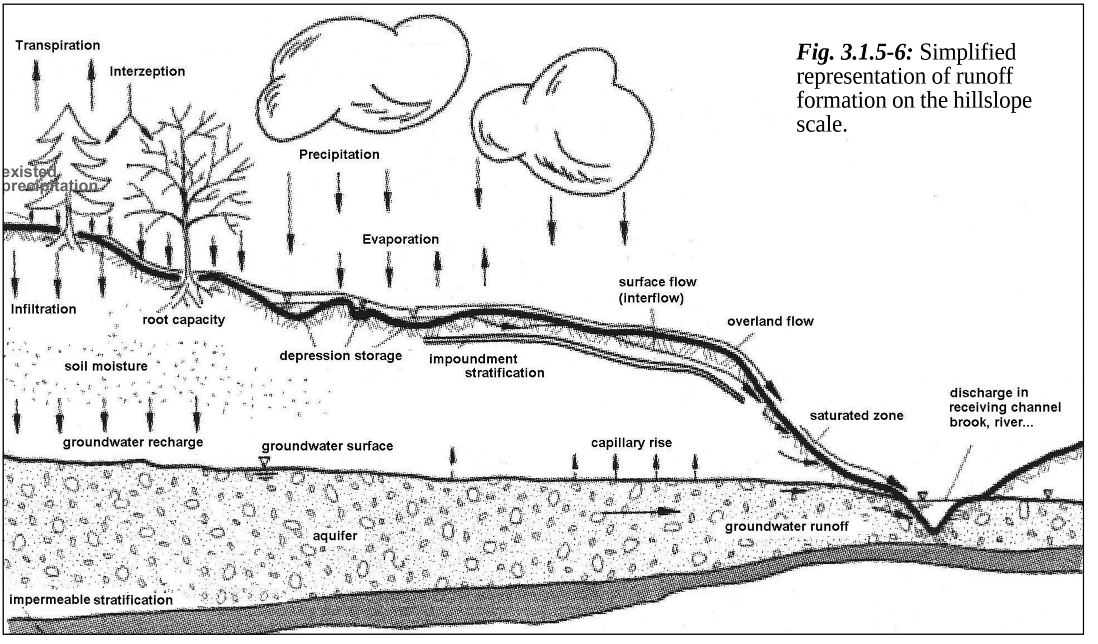

Fig. 3.1.5-6: Simplified representation of runoff formation on the hillslope scale.

hydrograph at the outflow of the catchment depends mainly on the magnitude of the flood event and on the size of the catchment. In general, the following relations apply: (1) With increasing magnitude/return period of the precipitation event the influence of areal characteristics of the catchment decreases. (2) With increasing catchment size the influence of areal characteristics of the catchment are shifting into the background against the characteristics of the drainage network. Basically, it is obvious that land use (and its changes) have effective influence only on such processes of runoff generation that are controlled by the condition of the ground surface. This applies above all to the infiltration-excess overland flow. The other processes are dominated by the conditions of the underground and are thus hardly affected by land-use changes. The above-mentioned areal catchments relate – in contrast to the drainage network – to all physiographic factors that influence the runoff generation.

In the following, anthropogenic interventions like rural-land consolidation or urbanisation as well as targeted measures aiming at minimising or retarding runoff generation during flood events are counted among these characteristics, even if they relate to linear landscape elements such as roads or field-border strips.

Modelling land-use impacts on the mesoscale

Here, the results of a study are presented that examined the impacts of land-use changes on flood generation in mesoscale river basins by means of hydrological models. The process-oriented modelling approach used the deterministic distributed model WaSiM-ETH (SCHULLA 1997). For better consideration of the influence of land use on flood generation, the model was supplemented by NIEHOFF (2002) with several aspects of the generation of surface runoff, such as the explicit inclusion of macropore flow, clogging, sealed surfaces with sewer drainage, and the effect of decentralised water retention.

Three mesoscale catchments of very different land uses were selected for this study in the German part of the Rhine basin: One with intensive agriculture (River Lein near Heilbronn, 115 km²), one that is densely populated (River Körsch near Stuttgart, 127 km²), and a forested one (upper Lenne River, 455 km²).

FRITSCH (2002) established for all of the three study areas spatially detailed land use scenarios regarding urbanisation, abandonment of arable land, and reforestation. In the Lein river basin, the impacts of different scenarios of changed management practices within the existing land uses were determined (e.g. mulching on erosion-prone fields or the decentralised retention of surface runoff from paved surfaces in settlements).

The hydrological modelling exercise was performed separately for about five convective heavy-rainfall events and five advective ones (return periods between 1 and 8 years) in the period 1985–2000. In the catchment of the River Lenne, floods were caused exclusively by long-lasting advective rainfalls in this period.

The results of this study were documented in detail by NIEHOFF (2002). In the following, only some examples of hydrological model outputs of the three catchments are summarised:

- An increase in settlement areas in the Lein catchment by 50% would show very different consequences in dependence on the meteorological boundary conditions. According to the simulation, even flood events of the same return period of three years will produce variations in the increase of the flood maximum between 0% for a long-lasting advective precipitation event with high antecedent soil moisture and nearly 30% for an intensive local thunderstorm with low antecedent moisture.
  The computed increase in the runoff volume in an extreme scenario with a 50% expansion of settlements ranges in the study areas between 5 and 55% for convective precipitation and remains below 2% for advective events. The particularly low effects in the forested Lenne catchment are plausible in view of the geomorphologic conditions and the characteristics of advective precipitation that caused floods there.
  Table 3.1.5-2 gives an overview of simulated changes in the runoff maxima and volumes in all three study areas as a consequence of an assumed 50 % expansion of settlements.
- The floods, which occurred in the Lein catchment in the years 1983, 1988, and 1990 after cyclonal weather situations or advective precipitation, have also contributed to floods in the River Rhine. The influence of a 50% expansion of settlement areas that was simulated for these events in the Lein catchment varies in a rise of the flood peak between 0% to 4%.
- The Lenne catchment also illustrates that – against the widely held opinion – forest cover is not per se a sign of little contribution to flood generation. It is a fact that natural forests have higher water-storage capacity in their vegetation (interception, storage in the litter layer) than other land uses and that forest soils often have good infiltration properties. However, since the water storage by vegetation has little relevance for the generation of floods, and forests in the uplands often grow on shallow soils, forests – especially in combination with less pervious hardrock underground – are predestined for rapid subsurface runoff formation.
- In principle, artificial infiltration of the runoff from sealed surfaces is subject to the same restrictions like those that have been formulated for the impact of surface sealing itself. This was proven by simulations of the Lein catchment. Infiltration facilities are more effective when intensive convective rain falls and antecedent soil moisture is low, but they are less beneficial in case of prolonged advective precipitation with high antecedent moisture, because then the infiltration capacity of the natural soils becomes exhausted just like the capacity of the artificial infiltration facilities.

Table 3.1.5-2: Simulated increase in runoff due to an assumed 50% expansion of settlements for different types of precipitation and different catchments.

	Changes in			
	Maximum Runoff [%]		***Runoff Volume [%]***	
	Convective Events	***Advective Events***	***Convective Events***	***Advective Events***
Lein	20– 30	0–4	19–23	< 1
Körsch	30– 60	15–25	4–55	< 2
Lenne	–	< 1	–	< 1

- The flood-reducing effect of mulching is also mostly rather small and is often overestimated, because the evidence is based on micro-scale measurements with very intensive sprinkler irrigation. More details are presented by Bronstert et al. 2003a.

The results of the modelling effort prove that generalised statements on the influence of land use on flood generation are not meaningful, because the effects are strongly dependent on climatic and physiographic boundary conditions and on the spatial scale applied. Usually, the significance of rainfall intensity for flood generation is very high, but it is often not given due consideration. Only very intensive, i.e. convective precipitation events have noteworthy influence on the emergence of infiltration-excess overland flow and become relevant for the issue of land-use changes. Convective precipitation is of negligible significance for flood generation in the large river basins of Central Europe because of their local character. In the case of advective heavy precipitation (low intensities, wide areal coverage and long duration) land use is of low or even negligible relevance, because these types of precipitation trigger nearly exclusively subsurface runoff processes that are hardly influenced by the ground surface. As floods in the major rivers in Central Europe are usually caused by advective precipitation, land-use changes have secondary significance for these large catchments.

The findings gained from hydrological modelling are not limited to the catchments of the rivers Lein, Körsch, and Lenne. Regionalisation methods, simplified hydrological modelling approaches for large areas, and coupled hydraulic models allow to quantify the degree of land-use changes for large river basins like that of the River Rhine, and they bring it into a relation with the consequences of other anthropogenic activities like the effects of river training or the controlled flooding of polders. The interested reader is referred here to the study of the Commission for the Hydrology of the River Rhine (Bronstert et al. 2003b) ♦