MULTI-SCALE MODELLING OF LAND-USE CHANGE AND RIVER TRAINING EFFECTS ON FLOODS IN THE RHINE BASIN


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ABSTRACT

Land-use changes effects on floods are investigated by a multi-scale modelling study, where runoff generation in catchments of different sizes, different land uses and morphological characteristics are simulated in a nested manner. The macro-scale covers the Rhine basin (excluding the alpine part), the upper meso-scale covers various tributaries of the Rhine and three lower meso-scale study areas (100–500 km$^2$) represent different characteristic land-use patterns. The main innovation is the combination of models at different scales and at different levels of process representation in order to account for the complexity of land-use change impacts for a large river basin.

The results showed that the influence of land-use on storm runoff generation is stronger for convective storm events with high precipitation intensities than for long advective storms with low intensities. The simulated flood increase at the lower meso-scale for a scenario of rather strong urbanization is in the order of 0 and 4% for advective rainfall events, and 10–30% for convective rain storms with a return period of 2–10 years.

Convective storm events, however, are of hardly any relevance for the formation of floods in the large river basins of Central Europe, because the extent of convective rainstorms is restricted to local occurrence. Due to the dominance of advective precipitation for macro-scale flooding, limited water retention capacity of antecedent wet soils and superposition of flood waves from different tributaries, the land-use change effects at the macro-scale are even smaller, for example at Cologne (catchment area 100 000 km$^2$), land-use change effects may result in not more than 1–5 cm water level of the Rhine. Water retention measures in polders along the Upper and Lower Rhine yield flood peak attenuation along the Rhine all the way down to the Dutch border between 1 and 15 cm. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: land-use; river training; environmental change impacts; Rhine; scale; floods; flood management

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INTRODUCTION

The frequent occurrence of extreme flood events in the last decade has brought up an ongoing debate about the human impact on this phenomenon (e.g. Kundzewicz and Takeuchi, 1999; Longfield and Macklin, 1999; Bronstert et al., 2002; Bronstert, 2003; Pfister et al., 2004; Gebremeskel et al., 2005). There is no doubt that both the catchments and the river systems in large parts of Europe and elsewhere have undergone major changes in the past, and these environmental changes may have altered storm runoff generation and flooding regimes. However, due to
the diversity of the processes and factors involved, so far the extent of their consequences on flood generation can only be estimated. The high relevance of the flood risk issue and the large uncertainty involved give rise to two important questions:

To what degree do environmental changes—that is land-cover and river training— influence the flood situation in large river basins?

To what degree can flooding be mitigated by water retention measures both in the landscape and along the river courses?

The answers to these questions are of particular importance for large rivers with densely populated and industrialized shores, which are prone to a very large potential damage due to possible inundation. The river Rhine is the most prominent example of such kind of a river in Central Europe, which lead to the ‘Rhine action plan for flood defence’ (ICPR, 1998), where the implementation and evaluation of flood-reducing measures both along the river and within the catchment area are key components of future flood risk management. Following the severe flood events along the Rhine in 1993/94 and 1995 this plan has been brought up to reduce flood-related risks in the Rhine basin by reducing flood stages and damage potential, increase awareness of flooding and improving the system of flood forecasting.

A scientifically sound answer to the questions raised above requires the quantification of storm runoff generation, water retention and flood wave propagation processes at different scales and under different conditions. On the one hand, it is necessary to identify and to quantify the most important runoff generation processes during periods of heavy precipitation and the effects of anthropogenic measures on these processes. This involves both a possible reduction or an increase of the runoff produced or retained water volumes through anthropogenic activity, such as urbanization, farming or forest management. On the other hand, it is essential to quantify the transformation velocity and attenuation effects of a flood wave which propagates through the channel system. This involves the study of the channel hydraulics, including effects of flood wave retention by upstream reservoirs or river polders along the stream and possible superposition of flood waves from different tributaries.

The necessity to investigate both hydrological processes at the catchment scale (runoff generation) and river hydraulics including retention in polders (flood wave propagation) has been pointed out by the authorities in charge of flood management in the Rhine area, see, for example Krahe et al. (2002, 2004). This leads to the requirement of a multi-scale assessment.

Surface runoff generation processes can be observed best at the micro- or field-scale, such as hillslopes or headwater catchments. However, the variability of surface processes at that scale is rather large and runoff generated by subsurface processes cannot be assessed at that scale. This is the main reason why it is necessary to quantify runoff generation processes and the possible impacts of anthropogenic activity by means of a process-oriented hydrological model and at a spatial scale where both surface and subsurface runoff generation processes are relevant, but where the effects of flood wave propagation do not (yet) govern the discharge rate of the catchment outlet. Hence, the hydrological lower meso-scale ranging from 100 to 1000 km² (according to the definition of Becker, 1992) has been chosen for that purpose.

The discharge conditions of large rivers are governed by the effects of flood wave propagation in combination with retention of flood volumes in upland reservoirs and/or in flood polders. Therefore, a comprehensive assessment of land-use change effects on discharge conditions at the hydrological macro-scale (i.e. on the flood levels of the large rivers), requires a thorough analysis and quantification of the river hydraulic processes, too.

A detailed assessment of runoff generation processes at the lower meso-scale and river hydraulics at the macro-scale cannot be linked directly at the macro-scale. First, runoff generation processes show a high variability in time and in space, which is hardly educible in a comprehensive manner for large areas. Second, the data situation at the macro-scale usually does not allow the simulation of runoff generation processes at a completely physical basis, because information like soil properties, hydrogeological conditions, hydrological connectivity are not available in the needed resolution.

Thus it is necessary to bridge these two scales, that is to establish a less complex hydrological model at the upper meso-scale, which is capable of roughly accounting for the changes in the runoff generation due to land-use changes and that can be used to cover the whole catchment area and to provide hydrographs at each input node of the river system simulated by the hydraulic model. One key question in that respect is how to represent the effects of
land-use change into this upper meso-scale model, that is the regionalization of the process knowledge gained at the lower meso-scale into the conceptual model of the upper meso-scale. A possible way is to drive a statistical–empirical relationship, based on the results of the detailed model.

The multi-scale scheme sketched above has been chosen as the conceptual backbone of the research presented in this article. Detailed simulation studies of runoff generation processes possibly altered by environmental changes have been conducted in three different lower meso-scale catchments (different physiographic conditions; different type and degree of anthropogenic influence) by means of a physically based, process-oriented hydrological model. A rough but a real exhaustive simulation of the land-use impacts has been performed for the whole basin under study, where the information about the influence of runoff generation processes was derived from the process-oriented model. Finally, the main river system (i.e. the Rhine River and its main tributaries) has been modelled by a state-of-the-art hydraulic model, including effects of flood retention in polders.

The results will serve as sound scientific figures about a possible flood risk increase caused by land-use changes or a flood risk decrease induced by specific measures like decentral urban storm water retention or the flooding of polders. The spatial scale addressed here ranges from the lower meso-scale (from about 100 km²) to the macro-scale (about 100 000 km² and more).

THE STUDY AREA

This study is restricted to the Rhine basin between Maxau (Southwest Germany) and the German/Dutch border at Lobith (Figure 1) and covers an area of about 110 000 km², that is the alpine part of the basin is not a part of this investigation. This catchment has been subdivided into 95 sub-catchments, covering the main tributaries Neckar, Main, Nahe, Lahm, Moselle, Saar, Erft, Sieg, Ruhr and Lippe (Figure 1), for which the conceptual model was applied. Nested in the Neckar and Ruhr catchments, three lower meso-scale catchments (catchment area between ca. 100 km² and 500 km², see Figure 1 for their locations within the Rhine catchment) have been chosen to study the process changes due to land-use changes: the predominantly agricultural Lein (part of the Neckar basin), the heavily urbanized Körsch (part of the Neckar) and the forested Lenne (part of the Ruhr) areas.

Lower meso-scale

As indicated before, possible impacts of land-use changes on processes of storm runoff generation were investigated on three different catchments (within the Rhine basin) at the lower meso-scale covering an area between 100 and 500 km². They represent different characteristic geomorphologic types and different land-use patterns with either dominantly urban, agricultural or forest use (see Figure 2):

- Situated in SW-Germany, the Lein catchment is characterized by a gently sloping terrain that reaches from an altitude of 160–350 m a.s.l. The catchment drains an area of 115 km². Geologically the area is structured by marl and gypsum, which are partly covered by a loess stratum of 20 m thickness. The soils are predominantly represented by Luvisols and Cambisols, which provide good cultivation conditions for crop land. This is reflected by 60% of agricultural land-use. Nevertheless this area has experienced a decided increase of settlement due to its vicinity to a prospering industrial region.
- The 127 km² sized catchment of the Körsch is characterized by the Filder Plateau, which is drained by the small creek Körsch. The soils have evolved from marl and sandstones to fertile Luvisols, because of a 4–5 m thick loess stratum. The proximity to the city of Stuttgart has enormously influenced the land-use in the catchment of the Körsch. The area is characterized by a fast growing settlement and industrial development with up to almost 30% expansion that spreads into a former rural landscape that was (and partly still is) used intensively for agriculture.
- The upper Lenne catchment (455 km²) represents a typical highland area, situated in mid-west of Germany. It is characterized by steep slopes that range from 300 to 841 m a.s.l. The geology is dominated by clay-schist, which provides low reaching Cambisols at the slopes and floodplains in the valley. The area is covered by over 65% forest, only 5% settlement and 10% meadow. Land-use did not change much in the past decades in this area, because of its remote location.
Upper meso-scale

These three lower meso-scale catchments are nested within larger sub-catchments of the Rhine, for example the Lein and the Körsch are tributaries of the Neckar, and the Lenne is a tributary of the Ruhr (see Figure 1). The whole modelled region (between Maxau at the Upper Rhine and the Dutch/German border) has been subdivided into 95 such lower meso-scale basins and they form the main subbasins of the Rhine: Neckar, Main, Nahe, Lahn, Mosel, Sieg, Ruhr and Lippe (see Figure 1 and Table I).

Macro-scale

The whole Rhine basin exhibits rather contrasting physiographic conditions. Covering 185,300 km², the basin extends from the Swiss Alps to the North Sea, with altitudes ranging from 0 to above 4,000 m a.s.l. and a total length of 1320 km. In its upstream alpine parts, the Rhine basin receives up to 2,000 mm of precipitation per year, with
Figure 2. Maps of the land-use in the Körsch, Lein and Lenne subbasins. It can be clearly seen that the Körsch has experienced strong urbanization, the Lein is dominated by arable land, and the Lenne by forest with little settlements (Fritsch, 2002). This figure is available in colour online at www.interscience.wiley.com/journal/rra

Table I. Characteristic data of the most significant Rhine tributaries and major gauges of the Rhine in the study area

<table>
<thead>
<tr>
<th>River</th>
<th>Gauging station</th>
<th>Area (km²)</th>
<th>MQ (m³ s⁻¹)</th>
<th>MHQ (m³ s⁻¹)</th>
<th>HQ (m³ s⁻¹)</th>
<th>Observation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhine</td>
<td>Maxau</td>
<td>50 200</td>
<td>1260</td>
<td>3100</td>
<td>4540</td>
<td>4.06.99 1931–2000</td>
</tr>
<tr>
<td>Neckar</td>
<td>Heidelberg</td>
<td>14 000</td>
<td>135</td>
<td>1180</td>
<td>2700</td>
<td>22.12.93 1951–2000</td>
</tr>
<tr>
<td>Main</td>
<td>Raunheim</td>
<td>27 900</td>
<td>196</td>
<td>932</td>
<td>1980</td>
<td>30.01.95 1966–1989</td>
</tr>
<tr>
<td>Rhine</td>
<td>Kaub</td>
<td>103 488</td>
<td>1650</td>
<td>4220</td>
<td>7200</td>
<td>29.03.88 1931–2000</td>
</tr>
<tr>
<td>Lahn</td>
<td>Kalkofen</td>
<td>5900</td>
<td>46.7</td>
<td>384</td>
<td>840</td>
<td>10.02.46 1936–2000</td>
</tr>
<tr>
<td>Mosel</td>
<td>Cochem</td>
<td>28 100</td>
<td>315</td>
<td>2090</td>
<td>4170</td>
<td>22.12.93 1931–2000</td>
</tr>
<tr>
<td>Sieg</td>
<td>Menden</td>
<td>2900</td>
<td>54.1</td>
<td>552</td>
<td>1050</td>
<td>07.02.64 1965–1989</td>
</tr>
<tr>
<td>Rhine</td>
<td>Cologne</td>
<td>144 232</td>
<td>2110</td>
<td>6390</td>
<td>10 900</td>
<td>30.01.95 1931–2000</td>
</tr>
<tr>
<td>Ruhr</td>
<td>Hattingen</td>
<td>4500</td>
<td>69.7</td>
<td>528</td>
<td>907</td>
<td>01.01.94 1968–1989</td>
</tr>
<tr>
<td>Lippe</td>
<td>Schermbeck</td>
<td>4900</td>
<td>46.2</td>
<td>246</td>
<td>370</td>
<td>30.01.95 1965–1995</td>
</tr>
<tr>
<td>Rhine</td>
<td>Lobith</td>
<td>160 800</td>
<td>2280</td>
<td>6610</td>
<td>11 900</td>
<td>30.01.95 1931–2000</td>
</tr>
</tbody>
</table>

MQ, mean discharge; MHQ, mean annual maximum discharge; HQ, maximum discharge during the observation period.

precipitation falling as snow in seasonal average above 3.050 m a.s.l. The German and French parts of the Rhine basin further downstream are characterized by a temperate oceanic climate that is gradually changing into a more continental climate from northwest to the east and southeast. Annual rainfall ranges from 1.100 to 570 mm in the German part of the Rhine basin.

The Rhine has a mean annual discharge of 2490 m$^3$ s$^{-1}$ at its outflow into the North Sea (Herschy and Fairbridge, 1998). Its hydrological regime is largely influenced by the spatio-temporal distribution of rainfall, snow storage and snow melt in the Alps and the Central German Uplands and Eastern French Highlands (Vosges Mountains) further North (Middelkoop et al., 2000). The regime of the Rhine in Switzerland is of pluvio-nival type. Maximum runoff of the alpine rivers is observed during summer, with the melting of the stored winter snow cover. Water is temporarily stored in the alpine border lakes that have a smoothing effect on the Rhine discharge. Downstream of Basel, the pluvial regime of the Rhine increases gradually and high discharges are monitored in the winter season downstream of the Mosel confluence.

Floods along the river Rhine can constitute a major hazard in different reaches of the stream (Smith and Ward, 1998). Due to the heterogeneity of the meteorological conditions and the heterogeneous physiographic conditions, different rainfall patterns can result in different flood hydrographs, even when the total basin rainfall is very similar. Therefore, flooding in the Rhine catchment may not imply covering the whole river stretch.

The river system contains both regulated (dammed) and free flowing river stretches. The Neckar, Main and Mosel have been dammed by a cascade of barrages, which can influence minor floods. When discharges are high, the weirs in these rivers have to be opened so that the barrages are no longer effective. In contrast, the Saar (tributary to the Mosel, see Figure 5) dams cover the entire discharge regime.

In terms of general flooding conditions, the investigated river system can be classified into two categories. The valleys of the most Rhine tributaries and the Middle Rhine are cutting through the Central German Uplands. That is why in these parts of the basin in flood cases an overtopping of the river banks inundates only rather narrow strips of land, rarely exceeding a width of 100 m on each riverside. Flood-protection dikes in these parts do exist only on short stretches. On the other hand, along the rather flat areas of the Upper and the Lower Rhine, there were wide flood plains, whose average width was 4 km on the Upper Rhine and up to tens of kilometres on the Lower Rhine.

Almost all rivers in these parts of the basin have been straightened during the last century or even before. In many parts, the active floodplains have been reduced through the construction of levees, dikes and other structures, changing the discharge regime. Ebel and Engel (1994) have evaluated the loss in floodplain areas to as much as 70%. The main dikes of this dike system should protect the hinterland against floods with a return period of between 100 and about 500 years. However, at least in the area of the Upper Rhine, the protection level today is beneath a return period of 100 years, because the flood stages have increased due to the mentioned river training measures, in particular due to the construction of a cascade of 10 barrages and the corresponding canalization of the river between the Swiss/German border and Iffezheim (a river section of about 200 km length) after the 2nd world war.

Quite many measures along the Rhine and its main tributaries have been proposed and some of them have already been implemented in order to regain retention space in case of floods. The total retention volume which can be gained by those measures sums up to $145 \times 10^6$ m$^3$ and is described more in detail in Subsection 'Scenarios of river training measures'.

The catchment of the study area between Maxau and Lobith (110 000 km$^2$) is characterized by different topographic structures, where the elevation ranges from about 1000 m a.s.l. in the southeastern border of the main sub-catchment and the black forest area in the southwestern part of the Neckar basin down to 10 m a.s.l. in the Lower Rhine district. Different parts of the basin have different dominant land-use structures. This ranges from a predominantly forest cover, for which the Sieg and the Lenne sub-catchments (see Section 'Lower meso-scale') are typical examples in which the forest cover accounts for almost two-thirds of the area, to catchments that are dominated by urban land-use, as, for example in the Lower Rhine district, whose settlements, infrastructure and industrial areas cover up to 38% of that area. The general highly industrialized and populated Rhine basin has undergone many land-use changes during the last century. Those land-use patterns that are important for the flood occurrence include more features than just the common classifications of forested, agricultural or urban lands. With respect to land-use changes in the catchment the following general statements can be made:

- The forest area has slightly increased in the last century;
urbanized areas in the Rhine basin have increased significantly (at the expense of agricultural areas) and are expected to increase further, for example from 11.8% in 1997 to 13.4% in 2010 (Fritsch, 2002);

- agricultural lands are more and more artificially drained since 1945;
- re-allocation and consolidation of agricultural area has induced modifications (more rationalized and mechanized) of arable land management (Bronstert et al., 1995) and subsequently altered some hydrological processes in those areas.

MODELLING STRATEGY

Overview of the multi-scale modelling strategy

An interdisciplinary and nested multi-scale modelling approach was chosen through the combination of models for different purposes at different spatial scales. This allows the comparison of different land-use impacts and the effects of river training activities, including the retention capacity in rivers and flood plains on the discharge conditions of the Rhine. Special attention has to be paid to the coupling of catchment hydrology and flood wave propagation as well as to the transfer of land-use scenarios into the structure and parameterization of the hydrological models. Figure 3 shows a scheme of the interaction of different models at different scales, where the model names are given in capital letters with the main, scale-specific modelling concepts in brackets (left), associated spatial scales in the rectangular boxes (centre) and model approaches for lateral runoff concentration or discharge runoff routing to bridge different scales in italic letters (right).

Modelling of land-use impacts on storm runoff generation at the lower meso-scale

Catchment runoff resulting from heavy precipitation is generated either through infiltration excess, subsurface stormflow, as well as saturation-excess overland flow or quick ground water flow. The discharge capacity is strongly dependent on the hydraulic conditions of the river system. Both runoff generation and river discharge conditions can be altered by human activities, such as agricultural practices, urbanization or river engineering measures. However, at the lower meso-scale flooding discharges are controlled mainly by runoff generation conditions (how
applying the process-oriented hydrological model WASIM-ETH (Schulla, 1997) on the three lower meso-scale catchments described above. These were selected because they represent different characteristic land-use patterns with either dominant urban, agricultural or forested structure. Spatially distributed scenarios of future land-use were generated based on regional analyses of land-use trends. WASIM-ETH was considered to be an adequate tool for this purpose and this scale, because it includes most of the processes relevant for runoff generation during heavy rainfall and/or snow melt. It considers the spatial distribution of catchment characteristics, and is based on fine-gridded spatial and temporal dynamics of climate variables, topography, soil properties, land-use and vegetation.

However, some model extensions had to be developed in order to represent appropriately the influence of urban area, land-cover and the unsaturated zone on infiltration processes. Infiltration is a crucial process in modelling runoff generation of a catchment. Particularly under extreme precipitation conditions it contributes strongly to the water being transferred to the river system, either directly by generating infiltration excess overland flow or indirectly by influencing the extent of saturated surface areas, thus causing saturation-excess overland flow. Various effects of the actual soil surface and land-cover conditions have to be accounted for to cover the whole range of possible infiltration capacity of the catchment. The developed extensions of WASIM-ETH focus on soil and land-cover characteristics, which either increase or reduce the infiltration capacity. Increasing effects are mainly due to the occurrence of macropores (Bronstert, 1999), reducing effects are due to a possible siltation of the soil. In addition, to account for urban hydrological effects, an extension was developed, which accounts for the connection of sealed surfaces to the sewer system and the possible local storm water retention in urban and agricultural areas.

WASIM-ETH was applied continuously with a time step of 1 day and a time step of 1 h during storm events. This short time step during flooding conditions was necessary to accurately simulate the occurrence of infiltration excess overland flow which is usually linked to high rainfall intensities during rather short periods (Bronstert and Bärdossy, 2003). The spatial resolution was 50 m grid length, which proved to be adequate to represent the heterogeneity of the land-use. Furthermore, at each grid, the fraction of sealed surface can be specified. Niehoff et al. (2002) give an overview of the model and its extensions and Niehoff (2002) provides a comprehensive documentation and several application and sensitivity examples for the different extensions. Table II gives an overview of the parameters to be supplied for each grid for the extended WASIM-ETH model to represent the relevant (land-use affected) processes of flood generation.

Regionalization of the runoff generating processes to the upper meso-scale

The transfer of the detailed information about the runoff generating processes to larger sub-catchments of Rhine tributaries (up to 2000 km²) covering the Rhine basin between Maxau and Lobith was approached by applying rather simple, conceptual hydrological model (extended HBV-model, see below) with a generalized parameter set, tailored to represent land-use features. This generalization is achieved by establishing a statistical relationship between the simulated land-use change impacts obtained from the WASIM-ETH model and the HBV parameters.

The HBV model (Bergström, 1995) is a semi-distributed conceptual model. It uses sub-catchments as primary hydrological units and is extended with a simple Muskingum flood routing to be used between the sub-catchments to model the runoff from the whole catchment. The sub-catchments can be further subdivided into homogeneous zones based on elevation, soil type, vegetation, etc. The runoff is computed for each zone within the sub-catchments using simplified conceptual routines of snow accumulation and snowmelt, soil moisture accounting and evapotranspiration. The generated runoff is then routed to the outlet of the sub-catchments using a lumped runoff concentration model schematized by a series of two reservoirs; a nonlinear upper reservoir that is fed by the runoff generated from the zones and a lower linear reservoir, which is fed by a constant percolation rate from the upper reservoir (Lindström et al., 1997). The outflow from the upper reservoir simulates the relatively fast runoff from the soil zone near the surface, while the outflow from the lower reservoir simulates the rather slower base flow component. The total outflow from both reservoirs is finally smoothed by a triangular transformation function.

Figure 4 shows a schematic overview of the structure of the extended HBV model. The standard HBV
parameterization has been partly extended to make specific use of terrain data (topography, river network, more detailed land-use classification, soil) available for the whole Rhine basin.

Some extension of the model structure was made to account for the effects of urbanization and higher intensity precipitation on the runoff generation. A component for sealed area was introduced and runoff generated from such areas is directly routed to the outlet of the sub-catchments using the transformation function without entering any of the reservoirs of the runoff concentration module. Furthermore, at higher precipitation intensities, infiltration from unsealed soil surfaces may be limited by the infiltration capacity of the soil and a possible siltation of the soil surface, as discussed in the previous section. In order to model this phenomenon, two more parameters were introduced: a threshold precipitation intensity \( P_{\text{thr}} \) and percentage of sealing during heavy precipitation intensity \( C_{\text{seal}} \). When the precipitation intensity exceeds the threshold value, part of the precipitation in excess of the threshold produces overland flow. The ratio of this overland flow to the precipitation in excess of the threshold value is defined as the percentage of sealing during heavy precipitation [Equation (1)]:

\[
q' = \psi_{\text{seal}}(P - P_{\text{thr}})
\]  

where \( q' \) is the infiltration excess direct overland flow and \( P \) is the actual precipitation intensity. Both parameters \( P_{\text{thr}} \) and \( \psi_{\text{seal}} \) have to be estimated through model calibration.

The model needs a set of digital data including elevation, river network, soil map and distribution of the land-use. In addition, monthly estimates of potential evapotranspiration of different vegetation covers and interception storage of forest cover, as well as estimates of the percentage of sealed area in urban land uses are required.

As the HBV model is a conceptual model, most of its parameters do not have a physical meaning and therefore they have to be estimated through model calibration against observed catchment response. The effect of land-use changes on the runoff generation can however only be estimated only if a relationship between the model parameters and the land-use characteristics of the catchment is established. Parameters pertaining to zonal processes of runoff generation were estimated as functions of the land-use type or soil type within the investigated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topography</td>
<td>Grid altitude</td>
</tr>
<tr>
<td>Soil</td>
<td>Soil depth</td>
</tr>
<tr>
<td></td>
<td>Hydraulic conductivity</td>
</tr>
<tr>
<td></td>
<td>Saturation content</td>
</tr>
<tr>
<td></td>
<td>Macroporosity</td>
</tr>
<tr>
<td></td>
<td>Mean depth of the macroporous layer</td>
</tr>
<tr>
<td></td>
<td>Reduction of hydraulic conductivity of the soil surface in case of siltation</td>
</tr>
<tr>
<td>Urban areas</td>
<td>Settlement type</td>
</tr>
<tr>
<td></td>
<td>Fraction of sealed surface within a settlement</td>
</tr>
<tr>
<td></td>
<td>Capacity of urban retention reservoirs</td>
</tr>
<tr>
<td></td>
<td>Controlled outflow from urban retention reservoirs</td>
</tr>
<tr>
<td></td>
<td>Local catchment area of local storm water control measures (in urban or agricultural areas)</td>
</tr>
<tr>
<td></td>
<td>Retention capacity of local storm water control measures (both in urban or agricultural areas)</td>
</tr>
<tr>
<td></td>
<td>Maximum seepage from the storm water control measures</td>
</tr>
<tr>
<td>Land cover</td>
<td>Maximum interception storage</td>
</tr>
<tr>
<td></td>
<td>Soil cover index</td>
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<td>Leaf area index</td>
</tr>
<tr>
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<td>Root depth</td>
</tr>
</tbody>
</table>

Table II. Overview of the required parameters for the extended WASIM-ETH-model
Parameters of the lumped runoff concentration module were estimated for each sub-catchment using a transfer function of the catchment characteristics. The transfer function implemented has the form:

\[ p_k = G_{pk}(l_i, s_j, \text{size, slope, shape}) = \sum_{i=1}^{I} \lambda_{ki}l_i + \sum_{j=1}^{J} \gamma_{kj}s_j + \psi_A + \xi S + \mu \text{shape} \]  

where \( p \) is the model parameter, \( k \) is an index for the parameter (\( k = 1, \ldots, N \)), \( l \) and \( s \) are the relative areas corresponding to different land-use classes and soil types, respectively; \( I \) and \( J \) are the numbers of land-use classes and soil types, respectively; \( A \) is area of the sub-catchment, \( S \) is mean topographic slope within the sub-catchment. 'shape' is defined as the ratio between area of the sub-catchment and the square of the distance from the outlet of the sub-catchment to the farthest point in the sub-catchment.

The usual approach of estimating the parameters of the transfer function (\( \lambda, \gamma, \ldots \)) follows a two-step procedure. The model is first calibrated for many sub-catchments independently to obtain optimum model parameter sets and then the parameters of the transfer function are obtained using least squares from Equation (2). However, model
calibration results in only a single realization among many parameter sets that lead to similar model performance. Therefore, the relationship established between the model parameters and the catchment descriptors is likely to be weak, which may lead to a general problem of equifinality of model structures and parameter sets (Beven, 2000). A different approach was implemented in this work. The model parameters were first expressed in terms of the parameters of the transfer function using Equation (2), and then the models were calibrated simultaneously by varying the parameters of the transfer function (2). For this purpose sub-catchments with contrasting catchment properties were used. Thus, the model calibration directly yields the parameters of the transfer function, which remain the same for all sub-catchments. In this way, one can obtain quantitative information about the effect of different land uses on runoff generation.

The lower meso-scale sub-catchments modelled by the detailed process-oriented model WASIM-ETH (discussed in Subsection ‘Modelling of land-use impacts on storm runoff generation at the lower meso-scale’) were also incorporated in the simultaneous model calibration insofar that the calibration for these sub-catchments was made against the runoff resulting from WASIM-ETH simulations. In order to reproduce the effect of land-use
changes on the runoff generation yielded by WASIM-ETH, the results obtained for the different land-use scenarios were used together with the corresponding land-use distribution. For more details of this regionalization approach we refer to the paper by Hundecha and Bárđossy (2004).

Precipitation data had to be processed at an adequate spatial and temporal distribution within the study area. Time series for both precipitation and temperature from 1980 onwards were used: daily precipitation data from 1514 precipitation stations and daily maximum and minimum air temperatures from 313 climate stations from the German Weather Service, DWD, from which AN average daily air temperature was estimated. In case of stations with missing values, multiple linear regression was applied with up to 20 nearby stations to fill in the missing values.

For calibration of the hydrological meso-scale model, measured discharge values at the outlets of sub-catchments were processed. Therefore, the time series of measured daily discharge values were obtained for many gauging stations at the Rhine and its major tributaries. For most of the stations, the data covered the period from 1980 to 1998. Hourly data were also obtained for a number of stations for selected flood events. The simulation period for the regionalized model runs from 1982 to 1995. A split sample approach was implemented to calibrate and validate the model. The first 7 years were used for calibration and the remaining 7 years were used to validate the calibrated model, see Bronstert et al. (2003) for details.

Flood routing of the river Rhine and its main tributaries at the macro-scale

Modelling the propagation of the flood waves through the river Rhine and its main tributaries was achieved by applying the Kalinin–Miljukov approach (SYNHP-model, Homagk, 1995) to some important tributaries and the hydrodynamic model SOBEK (WL Delft Hydraulics, 1997) to the main tributaries and the river Rhine itself. This allows the river discharge dynamics to be simulated, including impacts of alterations of river bed (both changes in cross-section and longitudinal section) and retention effects from polders or over spilling into flood plains. Further simulated aspects are factors like river roughness or storage effects of groundwater in the aquifers connected with the river. The model SOBEK was applied for the Rhine stretch between Maxau and the Dutch border and the lower parts of the rivers Neckar, Main and Lahn, while SYNHP was applied for different retention scenarios and furthermore for the lower course of the main Rhine tributaries Mosel and Saar (see Figure 5).

The following procedure for the macro-scale flood routing modelling was executed:

1. Set-up of the model scheme: definition of river nodes, preparation of all required data of river geometry and hydraulic structures in the river (weirs), first estimation of roughness values, provision of inflow hydrographs at the upper boundary nodes and at lateral inflow junctions and provision of initial conditions. Figure 6 gives an overview of the model scheme for the main channel of the Rhine between Maxau and Lobith. Note that the lateral inflow hydrographs can result from river tributaries, or from catchment areas draining directly into the river stretches (‘direct catchment’, see Figure 6) or from groundwater interaction.

2. Calibration and validation of the model: The only calibration parameter for the hydraulic model was the river roughness (Manning’s $n$), where different values were assigned for the main river section and for the flood plains (forelands). First, the model was calibrated for stationary conditions and afterwards non-stationary conditions (e.g. various flood events) were used as a 2nd calibration step. For the stationary calibration recorded water-level of the Rhine, Main and Mosel Rivers various characteristic discharge conditions (high, mean, low water levels) were used. The non-stationary calibration used the recorded water-stage hydrographs of major floods on the Rhine such as the ones of 1983, 1988, 1993 and 1995. In Table III the flood events which were used for non-stationary calibration and validation are listed. The stationary and non-stationary calibration finally resulted in a rather good fit of measured and simulated water levels, that is for 90% of the simulation time an accuracy of at least $\pm 20$ cm (stationary calibration) and at least $\pm 10$ cm (non-stationary calibration) was achieved at all gauges. More details and results of the calibration and validation procedure are given in the report of the BIG (2002).

3. Simulation of scenario conditions, such as variations of lateral inflow hydrographs (due to land-use change effects, provided by the meso-scale hydrological model), river training measures (in particular controlled retention in polders) and different meteorological conditions. The scenarios and the referring simulation results are presented below in Sections ‘Scenarios’ and ‘Simulation Results’.
Figure 6. Hydraulic model scheme for the Rhine main channel between Maxau and Lobith. The box lists the lateral inflow to the main Rhine stretches from ‘direct catchment’ areas along such stretches and from groundwater storages. This figure is available in colour online at www.interscience.wiley.com/journal/rra
To design land-use and land-cover scenarios the Land-Use Change Modelling Kit (LUCK) was applied (Fritsch, 2002) for the three catchments of the lower meso-scale and for selected sub-catchments of the upper meso-scale. LUCK realized land-use conversion based on an evaluation of the site characteristics of each pixel as well as its neighbourhood relationships. Typical land-use patterns and the influence of development axes like roads or railways are included in the analysis. These criteria form the potential of each pixel to become subject to changes. Since land-use changes happen sequentially the procedure tries to imitate this by an iterative procedure.

Land-use changes for the main land-use categories are considered within LUCK by three different modules for urbanization, agricultural and forested land-use changes. Possible changes in land-use follow a strict economic hierarchy ranking urbanization as the highest, followed by agricultural and by forest demand for land. It also takes into account the explicit geographic position and the interaction with different land-use types. Thus, LUCK provides a method for a spatial transformation of general (large-scale) trends of land-use changes into spatially distributed land-use patterns. The overall trends are obtained from external analysis.

LUCK has been validated using historical data (see Fritsch, 2002), which showed its capacity to design appropriate land-use scenarios. As an example for an urbanization scenario at the lower meso-scale, Figure 7 shows an urbanization scenario for the Körsch catchment. Due to the vicinity of Stuttgart to the Körsch catchment, a rather strong economic development in combination with a further increasing urbanization is expected in the future. Besides the demand for housing areas, the demand for industry areas is strong, resulting that land is a general scarce...
In order to simulate the effects of land-use changes on the runoff generation in the upper meso-scale (both for individual sub-catchments and for the whole basin), the referring hydrological model had to be applied to different land-use change scenarios that cover the whole study area. For that purpose, three different land-use scenarios for the whole catchment, focusing on urbanization and/or urban storm water management, have been developed:

1. Scenario D1 is based on a rather realistic scenario of about a further 10% expansion of urban areas in the Rhine catchment as projected by Dosch and Beckmann (1999),
2. Scenario D2 includes the increase of urban area of scenario D1 and, additionally, a planned project for controlled infiltration (retention) of urban storm runoff in 2500 km$^2$ urban areas, as recommended in the flood action plan of the International Rhine Commission (ICPR, 1998) and
3. Scenario D3 representing an ‘extreme scenario’ of a 50% increase of urban areas.

Scenarios of river training measures

The river training measures simulated in this study imply mainly the establishment of controlled flood retention polders at various locations along the upper and Lower Rhine. In general they are planned in parts of the Rhine flood plains which were regularly flooded before the flood-protection dikes were constructed. Most of the planned retention polders might be established by adding a dike in a certain distance from the current main dike resulting in a retention volume encompassed by the present dike near the main river and the new one. Besides such controlled retention polders, at some locations, a simple relocation of dike is planned (with demolishing the existing dike). This will enable the river to inundate a larger area of the flood plain then in the present state (with probably favourable ecological effects) but will not yield a controllable retention volume for flood management. The different planned measures for the Rhine between Maxau and Lobith are listed in Table IV, distinguishing between measures along the Upper and Lower Rhine. Their total retention volume sums up to 145 × 10$^6$ m$^3$. Note that the existing and planned flood retention polders upstream of Maxau (207.6 Mio m$^3$) have not been assessed in this study.

Scenarios of extreme meteorological conditions

The scenarios of land-use and river training measures were combined with three different scenarios of meteorological forcing, one observed large-scale extreme precipitation situation and two designed ‘extreme meteorological scenarios’ in order to apply the model system for meteorological conditions even more severe than the ones observed during the past:

1. Scenario M95: Meteorological forcing (in its observed spatial and temporal distribution) of January/February 1995 which caused a flood in the Rhine with a return period between 20 and 100 years (varying at different stretches of the river Rhine);
2. Scenario M95+: Meteorological forcing of January/February 1995 plus a linear increase in precipitation of 20%;
3. Scenario M95++: Meteorological forcing of January/February 1995 plus a linear increase in precipitation of 20% plus an additional pre-event snow water equivalent of 20 mm over the whole catchment.

These scenarios of meteorological forcing do not relate to some possible setting of the future climate conditions in the Rhine area. This means that they are not related to simulations of a possible future precipitation in the context of scenarios of greenhouse gas emissions due to a global change (IPCC, 2001). However, they are within the range of observed trends in precipitation over the Rhine catchment in recent decades. For example, Bronstert et al. (2002) reported on an increase in annual precipitation over the Rhine catchment in the last 100 years of about 10-15%. And statistical analysis of trends in winter precipitation over Europe by Schönwiese and Rapp (1997) showed a significant increase in Central and Northern Europe for the same period. That means that the precipitation scenario ‘M95+’ assumes a continuation of the trend observed in the last century. Snow-melt events over the Central German Uplands and Vosges Mountains in combination with heavy and long-lasting rainfall periods are known to
trigger the most severe flooding conditions. Thus we constructed an extreme snow-melt/rainfall scenario ‘M95++’, which assumes the same average precipitation conditions as ‘M95+’ combined with a pre-event snow pack in the central mountain ranges.

**SIMULATION RESULTS**

**Lower meso-scale**

As an example for the modelling of the impact of urbanization on storm runoff generation at the lower meso-scale, in the following the simulated response to an increase in urban areas of 10% and 50% respectively in the Lein catchment is described. In the Lein catchment, such an increase corresponds to a growth of these land-use types from 7.4% of the catchment area to 8.1% and 11.1% respectively.

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**Table IV. The planned retention measures along the Rhine below Maxau**

<table>
<thead>
<tr>
<th>Retention area</th>
<th>Operation mode</th>
<th>Volume (×10⁶ m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Position (Rhine km mileage)</td>
<td></td>
</tr>
<tr>
<td><strong>Upper Rhine</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wörth/Jockgrim/Neupotz</td>
<td>368</td>
<td>16.2 (12 + 4.2)</td>
</tr>
<tr>
<td>Elisabethenwört</td>
<td>381.3–383.0</td>
<td>11.9</td>
</tr>
<tr>
<td>Mechtersheim</td>
<td>388.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Rheimschanzinsel</td>
<td>390.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Flotzgrün</td>
<td>392.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Kollerinsel</td>
<td>409.9</td>
<td>6.1</td>
</tr>
<tr>
<td>Waldsee/Altrip/Neuhofen</td>
<td>411.5</td>
<td>9.1 (7.9 + 1.2)</td>
</tr>
<tr>
<td>Petersau/Bannen</td>
<td>436</td>
<td>1.4</td>
</tr>
<tr>
<td>Worms Bürgerweide</td>
<td>438</td>
<td>3.4</td>
</tr>
<tr>
<td>Mittlerer Busch</td>
<td>440</td>
<td>2.3</td>
</tr>
<tr>
<td>Bodenheim/Laubenheim</td>
<td>490</td>
<td>6.4</td>
</tr>
<tr>
<td>Ingelheim</td>
<td>517</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Total for Upper Rhine below the Maxau gauging station</strong></td>
<td></td>
<td>79.2</td>
</tr>
<tr>
<td><strong>Lower Rhine</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cologne-Langel</td>
<td>668.5–673.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Worringer Bruch</td>
<td>705.5–708.5</td>
<td>8</td>
</tr>
<tr>
<td>Monheim</td>
<td>707.5–713.5</td>
<td>6.9</td>
</tr>
<tr>
<td>Itter-Himmelgeist</td>
<td>723.5–727.5</td>
<td>2</td>
</tr>
<tr>
<td>Ilvericher Bruch</td>
<td>750.5–754.5</td>
<td>8.1</td>
</tr>
<tr>
<td>Mündelheim</td>
<td>760.5–769.5</td>
<td>3</td>
</tr>
<tr>
<td>Orsoy Land</td>
<td>797.5–803.5</td>
<td>10</td>
</tr>
<tr>
<td>Bislicher Insel</td>
<td>818.5–823.5</td>
<td>—</td>
</tr>
<tr>
<td>Lohrwardt</td>
<td>832.5–833.5</td>
<td>12.9 (10.3 + 1.6)</td>
</tr>
<tr>
<td>Grießherbusch</td>
<td>837.5–847.5</td>
<td>—</td>
</tr>
<tr>
<td>Bylerward</td>
<td>845.5–854.5</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total for Lower Rhine</strong></td>
<td></td>
<td>65.4</td>
</tr>
<tr>
<td><strong>Total volume of all listed measures</strong></td>
<td></td>
<td>Approx. 145</td>
</tr>
<tr>
<td><strong>Total polder volume (excluding the volume of dike relocations)</strong></td>
<td></td>
<td>Approx. 108</td>
</tr>
</tbody>
</table>

The kilometre milage (column 2) refers to the km values shown in Figure 6. *Controlled retention polder.
Figure 8 is a comparison of two typical flood types in the Lein catchment, one induced by advective circulation conditions (long lasting but less intense rainfall) and one by convective conditions (i.e. a summer thunderstorm: short rainfall with very high intensity). The Figure presents simulation results for present conditions as well as for the two urbanization scenarios. The comparison demonstrates that the increase in flood volume and peak runoff due to urbanization is much more distinct for the convective storm event than for the advective one, although the precipitation volume as well as the peak flow is in the same order of magnitude for both events and represents a return period of approximately 2–3 years in both cases. The markedly slighter effect on the advective event is the result of (1) higher antecedent soil moisture which levels differences in soil characteristics as well as (2) lower precipitation intensities which prevent an overflow of the sewer system.

This argument is also supported by a comparison of various advective events with different return periods, as it is shown in Table V. The comparison reveals a strong correlation between the impact of urbanization on runoff and the baseflow contribution to the flood event, which serves as an indicator for high groundwater levels and high soil moisture.

Another comprehensive source of information is the runoff components that are simulated for the different flood events (Figure 9). The two pie charts reveal pronounced differences in the dominating runoff-generation mechanisms depending on the event characteristics (rainfall intensities and pre-storm moisture conditions). The response to convective storm events is dominated by sewer overflow from sealed surfaces as well as a considerable amount of infiltration-excess mainly from agricultural areas. In contrast to that, for advective events subsurface flow processes and saturation-excess prevail.

Niehoff and Bronstert (2001) have presented other examples of modelling land-use change or surface condition impacts (such as urban storm water infiltration, agricultural storm water management or surface crusting of arable land). The results were similar in the sense that the impacts are generally much more pronounced in cases of

Table V. Increase in runoff volume and peak due to a 50% increase of settlement and industrial areas in the Lein catchment

<table>
<thead>
<tr>
<th>Year, month</th>
<th>Increase in runoff compared to present conditions</th>
<th>Simulated baseflow contribution to volume (%)</th>
<th>Duration (h)</th>
<th>Return period approx. (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum (%)</td>
<td>Peak (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>February 1990</td>
<td>3.4</td>
<td>3.7</td>
<td>19</td>
<td>150</td>
</tr>
<tr>
<td>December 1993</td>
<td>5.9</td>
<td>2.7</td>
<td>17</td>
<td>250</td>
</tr>
<tr>
<td>February 1997</td>
<td>3.9</td>
<td>2.7</td>
<td>19</td>
<td>150</td>
</tr>
<tr>
<td>December 1982</td>
<td>1.7</td>
<td>1.5</td>
<td>27</td>
<td>225</td>
</tr>
<tr>
<td>May 1983</td>
<td>0.6</td>
<td>0.9</td>
<td>39</td>
<td>300</td>
</tr>
<tr>
<td>March 1988</td>
<td>0.0</td>
<td>0.0</td>
<td>52</td>
<td>650</td>
</tr>
<tr>
<td>Mean</td>
<td>2.6</td>
<td>1.8</td>
<td>29</td>
<td>290</td>
</tr>
</tbody>
</table>

The events are sorted by the urbanization impact on runoff volume.
convective rainstorms than for advective rainstorms. A forest area, in contrast to a still widely spread opinion, does not necessarily mitigate floods. This is illustrated by the example of the Lenne catchment. Of course, normally a natural forest shows better storage conditions (interception, litter storage) than other land-cover types and the soils under forests quite often feature good infiltration conditions. But since forests in Central Europe often grow in mountainous regions with thin soils and low-permeable bedrock, the overall storage capacity of the soil is rather limited and these conditions often show subsurface storm flow processes.

The results of these simulations allow the derivation of general causal connections:

(1) Relevance of precipitation characteristics:
- Precipitation intensity: The influence of land-cover is stronger for convective events with high rainfall intensities than for advective events with mostly much lower precipitation intensities.
- Precipitation volume: The bigger the precipitation volume, the minor is the influence of land-cover on storm runoff generation.

(2) Relevance of the initial boundary conditions:
- The drier the catchment is at the beginning of the event, the greater is the influence of land-cover on storm runoff generation.

(3) Relevance of the infiltration conditions:
- If the magnitude of infiltration capacity is equivalent to the magnitude of precipitation intensity, then the influence of land-cover matters most for storm runoff generation.

(4) Relevance of geomorphology:
- If the permeability of the soil surface does not represent a limitation for infiltration, then the geological properties are the crucial factor for storm runoff generation. Consequently land-cover then only exerts a marginal influence on runoff generation.

(5) Relevance of event-scale:
- The magnitude of the peak discharge or its return period respectively is not a suitable indicator for the influence of land-cover on floods. The return period does not tell much about the meteorological boundary conditions of a flood nor does it provide an insight in the spatial distribution of storm runoff generation processes in a catchment.

Figure 9. Runoff components simulated with WASIM-ETH for the Lein catchment for five convective and six advective storm events with return periods between 2 and 8 years (Niehoff and Bronstert, 2001)
Relevance of the spatial and temporal scale:

- In meso-scale areas of up to several 100 km$^2$, both convective and advective rainfall events may cause floods. In the large river basins of Central Europe, floods normally occur as a consequence of widely spread and long-lasting cyclonic rainfall events—potentially in combination with snow melt. For this kind of events the influence of land-cover is smaller than for convective rain storms. In these large areas, convective rainfall events are of minor relevance, because of their local character.

Upper meso-scale

Similar results as in the lower meso-scale were obtained from the simulations due to increased urbanization in upper meso-scale catchments. Figure 10 shows the simulated discharges for the different land-use scenarios resulting from the observed meteorological conditions of a winter and a summer flood event within the Neckar catchment at Gauge Rockenau (12,665 km$^2$). In the present land-use situation, the urban area covers 15% of the catchment area and scenario D1 (see Section ‘Land-use change scenarios’) represents a growth to 16.5%, expected for the year 2010, while scenario D3 represents a purely hypothetical growth to 30%. Figure 10 shows that—in general terms—the effect of urbanization at this scale is rather small. Furthermore, one can see that urbanization effects are more pronounced for intense summer rainfall of shorter duration than for the less intense and longer duration winter rainfall, which confirms the previous results at the lower meso-scale. The different responses are mainly due to the difference in the antecedent soil moisture conditions and the infiltration processes as discussed already in the previous section.

Macro-scale

In Table VI a summary of the macro-scale simulation results is presented by listing the combined effects of land-use scenarios and meteorological scenarios. Note that all scenarios D1, D2 and D3 also account for the river training measures along the Rhine, presented in Section ‘Scenarios of river training measures’ (Table IV). The simulated differences in water levels (in cm) at five main gauging stations of the Rhine are given. The non-parenthetic values are due to the combined effects of land-use change (increase of urban areas) and river training (increase of flood-discharge retention in river polders). The values in parenthesis are due to land-use
change only (1st value) and due to river training only (2nd value). Positive numbers imply a decrease in water level, negative numbers imply an increase. From the differences in water levels listed in Table VI one can see that

- the increase of flood peak level due to a further moderate (realistic) increase of urbanized areas (D1) is very small (water level increase of 2 cm or less) and therefore almost negligible;
- the influence of the proposed management of urban storm water results in a very limited mitigation of flood peaks (water level decrease 2 cm or less) and therefore is almost negligible, too;
- water retention in flood polders (between Maxau and Lobith) has a stronger but still small effect (water level decrease of 3 cm or less for the M95 scenario, up to 10 cm for the M95+ and up to 17 cm for M95++. It is important to understand, that the consideration of the possible retention polders upstream Maxau would yield an additional reduction in the range of 10 cm, in particular for the Upper Rhine area;
- the unrealistic, extreme land-use scenario (50% increase of urban areas) would result in a water level increase of not more than 10 cm;
- the M95+ and even more the M95+++ scenario result in higher reduction of flood levels in case the flood polders are active. This is due to the fact that according to the operation rules, the flood polders are to be filled only if flood discharge exceeds the 200-year value. In January/February 1995 (M95) the flood discharge along most

<table>
<thead>
<tr>
<th>Rhine gauging station (km downstream Lake Constance)</th>
<th>Meteorological scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M95</td>
</tr>
<tr>
<td>Worms (444 km)</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>0 (0/0)</td>
</tr>
<tr>
<td>D2</td>
<td>0 (1/0)</td>
</tr>
<tr>
<td>D3</td>
<td>0 (1/1)</td>
</tr>
<tr>
<td>Kaub (546 km)</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>1 (-1/2)</td>
</tr>
<tr>
<td>D2</td>
<td>1 (-1/2)</td>
</tr>
<tr>
<td>D3</td>
<td>-5 (-7/3)</td>
</tr>
<tr>
<td>Andernach (614 km)</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>0 (-1/1)</td>
</tr>
<tr>
<td>D2</td>
<td>0 (0/1)</td>
</tr>
<tr>
<td>D3</td>
<td>-5 (-7/2)</td>
</tr>
<tr>
<td>Köln (688 km)</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>0 (-2/1)</td>
</tr>
<tr>
<td>D2</td>
<td>0 (0/1)</td>
</tr>
<tr>
<td>D3</td>
<td>-8 (-9/2)</td>
</tr>
<tr>
<td>Lobith (857 km)</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>2 (-1/3)</td>
</tr>
<tr>
<td>D2</td>
<td>2 (-1/3)</td>
</tr>
<tr>
<td>D3</td>
<td>-1 (-5/3)</td>
</tr>
</tbody>
</table>

D1: Current land-use conditions and a 10% increase of urban area.
D2: Current land-use conditions and increase of urban area (D1) plus controlled infiltration of urban storm runoff.
D3: Current land-use conditions and a 50% increase of urban area (‘extreme urbanization scenario’).
M95: Meteorological forcing (in its observed spatial and temporal distribution) of January/February 1995.
M95+: Meteorological forcing of January/February 1995 plus a linear increase of precipitation of 20%.
M95+++: Meteorological forcing of January/February 1995 plus 20% increase of precipitation plus an additional pre-event snow water equivalent of 20 mm.
Positive numbers imply a decrease in water level, negative numbers imply an increase. The non-parenthetic values represent the combined effects of land-use change and river training. The values in parenthesis are due to land-use change only (1st value) and due to river training only (2nd value).
stretches of the Rhine was below the 100-year value (Engel, 1996). That is why the polders were used only at a few stretches resulting in small water level reduction only.

CONCLUSIONS AND OUTLOOK

This study is an example of a multi-scale, process-oriented coupling of different models in order to simulate and evaluate the impacts of land-use and river training measures on the flood discharge of a large catchment. For the first time it was possible to give quantitative estimates for the impacts of land-use change and river training measures on the flood conditions for the river Rhine. Some exemplary results have been demonstrated above. The study as a whole is documented in the CHR report (Bronstert et al., 2003).

When assessing land-use effects on storm runoff generation, we consider it rather important to account not only for precipitation amount but also for the intensity of the rainfall. We have shown that this enables the distinction of different surface runoff generation processes, and thus, the identification of soil surface conditions effects on such processes. The conventional approach, assigning a runoff coefficient to different land uses, such as done, for example in the SCS-Curve Number Method (Maidment, 1993) or in the WETSPA-model (Gebremeskel et al., 2005) does not bear this option.

Some general results from the whole study are summarized in the following:

1. The influence of land-use on storm runoff generation in the meso-scale is stronger for convective storm events with high precipitation intensities than for long advective storm events with low precipitation intensities, because only storm events associated with high rainfall intensities are at least partially controlled by the conditions of the land-cover and/or the soil-surface.

2. An estimated—rather dramatic—further increase of urban areas of about 50% may result in an increase of a medium-size flood peak discharges (e.g. return intervals between 2 and 8 years) in catchments of the lower meso-scale:
   - Between 0% and 4% for advective rainfall events and
   - Up to 30% for convective rain storms.

3. The flood impacts in the macro-scale due to a more realistic urbanization scenario are in the order of 1–5 cm in the main channel, while the relative effects are even smaller for extreme rainfall amounts.

4. The decentralized storage, detention and infiltration of urban storm water yields reduction of flood peaks by the same order of magnitude as the increase due to urbanization in catchments of the lower meso-scale (see above).

5. Convective storm events, however, are of minor relevance for the formation of floods in the large river basin of the Rhine catchment because the extent of convective rainstorms is usually restricted to local occurrence. This conclusion is of rather high importance for flood management not only for the Rhine basin but probably also for other large river basins in Europe with similar climatic and morphological conditions.

6. The superposition of flood waves originating in different tributaries of the Rhine shows that the maximum effect of water retention in the macro-scale generally occurs in the rising limb of the flood wave in the main channel. The flood mitigation effect at the peak is considerably smaller.

7. Water retention measures in polders along the Upper and Lower Rhine under the given boundary conditions yield flood peak attenuation along the Rhine all the way down to Lobith between 1 and 15 cm (see Table VI). The optimized and co-ordinated control of the polders can result in a considerably stronger decrease of the peaks.
finally uncertainty due to an imprecise or at least inappropriate model structure. In this study, we did not aim to
analyse comprehensively or even to quantify these different uncertainties.

We tried to minimize uncertainty in the precipitation input, which is by far the most important meteorological
variable for flood generation, by using the highest available number of daily precipitation observations (from 1514
precipitation stations in the catchment) and to apply an interpolation scheme specifically adapted to large-scale
precipitation fields (see Hundecha and Bárdossy, 2004).

Our main intention was to setup a model system and structure which includes the relevant processes for
modelling land-use change impacts. Such processes are on the one hand infiltration and runoff generation related
processes, and on the other hand the routing and water retention processes in the channel system and linked polder
systems. Through introducing relatively small-scale process knowledge about land-use influences on runoff
generation and its transfer to larger scales we have reduced the corresponding structural uncertainty. The structural
uncertainty regarding river hydraulic processes has been approached by setting up a fully connected hydraulic
model for a large part of the river Rhine and the main tributaries. We have to emphasize that this has been the first
time that the river Rhine network has been modelled in such a comprehensive manner. Furthermore, the retention
processes in polders are included.

The parameter uncertainty was dealt with in a fairly conventional way. For example at various steps of the
modelling procedure the sensitivity of the model results to uncertain parameters has been assessed and the values of
the more sensitive parameters were varied in a plausible range. For the transfer of the small-scale process
knowledge to larger scales only the ‘best parameter estimates’ were used. We acknowledge that this is a somewhat
simple and incomplete handling of parameter uncertainty. However, we refrained from applying comprehensive
parameter analysis procedures, such as generalized likelihood uncertainty estimation (GLUE) (Beven and Freer,
2001), because first, such techniques applied to such a complex multi-scale and multi-mode system would require
an enormous computational effort (which—to our knowledge—has not yet been accomplished on such a large
river system anywhere else) and second, as mentioned earlier, our focus was not on the analysis parameter
uncertainty. Nevertheless, future research should also attempt to evaluate the uncertainties in the predictions of
change for such large and complex systems. It is of particular interest if methods can be developed to handle
uncertainty analysis in multi-model and multi-scale simulations and if these methods will allow us to evaluate the
limits of predictability.

We acknowledge that all the results and conclusions are derived from simulation results. However, the
simulations are anchored—at least partially—in observations. For example the simulation of land-use change
effects on storm runoff generation processes is consistent with both field experiments and observations of flood
events in small rural and urban catchments (Niehoff, 2002). Furthermore, the observed changes in flood routing
conditions along the Upper Rhine due to the river training measure along the river reach in recent decades are well
simulated by the flood routing model. These agreements in observations at different scales and simulation results
give us confidence in the performance of the modelling system. However, though we adapted a procedure to transfer
a small-scale process knowledge to a larger scale, the corresponding information base is still not fully satisfactory.
The regional equations for the estimation of the parameters of the conceptual upper meso-scale model were
developed for limited ranges of proportions of different land-use classes, as they were dictated by the prevailing
land-use distribution and the calibration was made against observation. The performance of the model in simulating
the runoff for slightly extrapolated proportions of land-use classes has been validated. For a large deviation,
however, the model simulation could be uncertain. Further work should be done to model the runoff for all ranges of
land-use distributions coupled with uncertainty analysis of model predictions.

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