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Impact of climate and land use changes on discharge and hydrological droughts

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Abstract

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In this study we applied the hydrological model SIMGRO to the Rhine basin. After the input data of the model was improved, the simulated discharges at Lobith were very close to the measured discharges. The model was then used to study droughts and the impact of climate and land use changes on discharges in the Rhine basin. We used the KNMI'06 climate scenarios to examine the changes in discharge and droughts. Furthermore extreme changes in land use were analysed, e.g. all cropland to grass and all cropland to forest. The results from the different scenarios show that climate change has a much larger impact on discharges and droughts than extreme changes in land use. In the last part of the study for the Neckar basin the spatial distribution of droughts in surface and ground water were explored. The discharge of the Neckar basin reacts immediately on precipitation, so as well the occurrence of droughts.

Keywords: SIMGRO, Rhine, Drought, Climate change, Land use change, River flow.

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Content

Preface

This report is the result of a study conducted by the first author for his Bachelor Thesis Land and Water Management at Van Hall Larenstein University of Applied Sciences. The first author worked for five months on this research with a lot of pleasure. The second and third authors were his supervisors during this period.

We would like to thank everybody who has helped and supported us during this research. Furthermore we would like to thank the CHR (International Commission for the Hydrology of the Rhine basin) for providing measured discharges and meteorological data.

A special thanks goes to Ladislav Holko from the Institute of Hydrology Slovak Academy of Science for his advice on model parameters for the snow module.

The study has been carried out with support from the Dutch Ministry of Agriculture, Nature Management and Food Quality. This research was also supported by the WATCH project, EC Priority Area 'Global Change and Ecosystems', contract number 036946. The research is part of the programme of the Wageningen Institute for Environment and Climate Research (WIMEK-SENSE).

Summary

The Rhine basin is a heavily industrialized and densely populated river basin. The basin is sensitive to hydrological extremes, such as floods and droughts, because of the clustering of functions. Floods have been studied extensively in the Rhine basin; droughts, however received less attention. To study droughts and to make predictions for the future, a hydrological model is required. This model should be capable of simulating low flows. SIMGRO is a model where the low flows are well simulated due to its physically based nature. The first steps in developing a SIMGRO model for the Rhine basin were taken by Querner (2009). This first model was built with available digital data and expert judgement.

The Querner (2009) model needed to be improved before it could be used for predictions and for studying droughts. The meteorological data (precipitation and potential evapotranspiration) were regionally differentiated over 134 regions, furthermore the land use data and lake levels in Switzerland were improved. The transmissivity of the subsurface (kD) and the soil moisture in the rootzone were spatially differentiated. Snow accumulating has been accounted for in the model and the degree-day method is used for the snow and ice melting. These improvements to the input data led to a model where at Lobith the simulated discharge is quite close to the measured for the low flows, but the peak flows are a bit underestimated. The snow component in the model improved for the Swiss part of the basin the discharges, but is still less than acceptable.

To examine the impact of climate change on discharges and droughts the KNMI'06 scenarios were used. In these scenarios, changes in temperature, precipitation, wind, and sea level for the climate in 2050, relative to 1990 are presented. Two (G+ and W+) of the four KNMI'06 scenarios assume that in 2050 there will be in Western Europe more westerly winds in winter and more easterly winds in summer. The consequences are wetter and milder winters and drier and warmer summers. With the use of these two scenarios (W+ and G+, delta change approach) the mean discharge at Lobith decreases by 5% (G+) to 8% (W+). Droughts will be more common in 2050. The Rhine at Lobith will have an increase in the number of drought days by 117% (G+) to 197% (W+). So droughts in river flow will be more common throughout the Rhine basin in the year 2050 (based on the assumption that the patterns in air circulation in Western Europe will change).

To examine the impact of land use changes on the discharges and droughts in the Rhine basin, two scenarios have been defined, one scenario in which all croplands will change in grasslands and one scenario in which all croplands will change in deciduous forest. For these scenarios the mean discharges changes at Lobith by -1.7% (crop to grass) to -4.0 % (crop to forest). The number of drought days in the discharge at Lobith increases for both land use change scenarios. In the crop to grass scenario the number of drought days increase by 21% and in the crop to forest scenario it increases by 46%. The results from the different scenarios show that climate change has a much larger impact on discharge and droughts than extreme changes in land use.

Part of the Rhine basin (i.e. Neckar basin) has been chosen for analyzing the spatial distribution of droughts. Not the whole basin has been chosen because of the limited time to conduct this research and the complexity within the entire Rhine basin. The discharge of the Neckar basin reacts directly to precipitation; droughts can therefore disappear fast. There is a clear spatial differentiation in the start and the duration of droughts in stream flow throughout the Neckar basin. The groundwater level returns each year back to the winter level (even after very dry years), which implies that no multi-year droughts develop.

1 Introduction

Background
The Rhine basin is a heavily industrialized and densely populated river basin in Western Europe. Next to that, the River Rhine is one of the busiest inland waterways in Europe. Because of this concentration of different functions, hydrological extremes (e.g. floods and droughts) have tremendous consequences for a wide range of sectors (Middelkoop et al., 2001). Examples of sectors that can be impacted by hydrological extremes are: agriculture, ecosystem services, inland navigation, industry, energy production (through cooling water), and drinking water.

In the Rhine basin floods have been studied extensively (De Wit et al., 2007, Pinter et al., 2006 and Disse 2004), on the other hand droughts received less attention. With possible changes in the future (e.g. change in climate and land use) the question arises what is the impact of these changes on the occurrence and the severity of droughts. To answer this question, knowledge is also needed on the occurrence of droughts in the past and the characteristics of those droughts (reference period). To gather this knowledge and to study the impact of changes on droughts, a large-scale hydrological model is needed.

In the past, several models have been developed for the Rhine basin. Examples of such studies are the VIC model recently applied on the Rhine basin (Hurkmans, 2009) and the HBV model (Te Linde, 2007). The disadvantages of these models is that they do not include all physical processes in detail, e.g. the lateral flow in the groundwater system and the detailed interaction between groundwater and surface water. The groundwater system plays a very important role in the simulation of low flows. SIMGRO is a physically-based spatially-distributed model where those physical processes are included in detail. The first steps in developing a SIMGRO model for the Rhine basin were taken by Querner (2009). This model was built with readily available digital data and expert judgement. The results from this first model were promising, and showed that it was possible to build a model for the Rhine basin with SIMGRO and to simulate the discharges in the basin reasonably well. But improvements had to be made to the input data of this first model to make it suitable for analyzing the effect of changes on discharge and droughts.

Objective and research question
This study should lead to an improved SIMGRO model for the Rhine basin. With that improved model, droughts from the past will be studied and analysis will be made on the impact of climate and land use changes on future droughts and discharges. This objective leads to the following research questions:
- Does the use of more detailed input data, on e.g. groundwater characteristics, lead to improved performances of the model for the Rhine basin?
- What are the effects of climate and land use changes on droughts and discharges in the Rhine basin?
- What are the characteristics of a drought in a sub-basin?

Research steps
The research is built up in different steps. The first step is the improvement of the input data of the existing SIMGRO model from Querner (2009). In the second step the model performance will be analyzed by comparing the simulated and measured discharge. In the third step the model will be used to study the effect of climate and land use changes on discharges and droughts. In the fourth step of the research the model will be used to analyze droughts in a sub-basin (the Neckar basin), this to understand the spatio-temperal development of a drought. Only one sub-basin has been chosen to analyze drought, because of the limited time to conduct this study and the complexity of the Rhine basin.
Outline

Chapter 2 gives a description of the SIMGRO model. In Chapter 3 the methodology to characterize droughts is introduced. Chapter 4 gives a description of the research area in combination with a description of the input data used for the SIMGRO model. Chapter 5 describes the improvements made to the input data. Furthermore, Chapter 5 shows the differences between measured and calculated discharges of the model with the improved input data. In Chapter 6 the different scenarios (climate and land use change) are introduced and the impact of the scenarios on discharges and droughts is presented. In Chapter 7 droughts are analyzed in the Neckar basin. The conclusions and recommendations can be found in Chapter 8.

2 Description of SIMGRO

2.1 Introduction

The interaction between groundwater and surface water has a large influence on minimum discharge (Querner, 2009). Therefore it is important for this study, were the focus is on droughts, to use a hydrological model were this interaction is included. The SIMGRO model (SIMulation of GROundwater flow and surface water levels) is a model in which this interaction between groundwater and surface water is integrated.

SIMGRO is a distributed physically-based model that simulates regional transient saturated groundwater flow, unsaturated flow, actual evapotranspiration, sprinkler irrigation, stream flow, groundwater and surface water levels as a response to rainfall, reference evapotranspiration, and groundwater abstraction. To model regional groundwater flow, as in SIMGRO, the system has to be schematised geographically, both horizontally and vertically. The horizontal schematisation allows input of different land uses and soils per nodal point, in order to model spatial differences in evapotranspiration and moisture content in the unsaturated zone. For the saturated zone various subsurface layers are considered (Figure. 2.1). For a comprehensive description of SIMGRO, including all the model parameters, readers are referred to Querner (1988, 1997).

2.2 Groundwater flow

In SIMGRO the finite element procedure is applied to approach the flow equation which describes transient groundwater flow in the saturated zone. A transmissivity is allocated to each nodal point to account for the regional hydrogeology. A number of nodal points make up a sub catchment as shown in Figure 2.1. The unsaturated zone is represented by means of two reservoirs, one for the root zone and one for the underlying soil. The calculation procedure is based on a pseudo-steady state approach, using generally time steps of one day. If the equilibrium moisture storage for the root zone is exceeded, the excess water will percolate towards the saturated zone. If the moisture storage is less than the equilibrium moisture storage, then water will flow upwards from the saturated zone (capillary rise). The height of the phreatic surface is calculated from the water balance of the subsoil below the root zone, using a storage coefficient. The equilibrium moisture storage, capillary rise and storage coefficient are required as input data and are given for different depths to the groundwater.
Evapotranspiration is a function of the crop and moisture content in the root zone. The measured values for net precipitation, potential evapotranspiration for a reference crop (grass) and woodland are input data for the model. The potential evapotranspiration for other crops or vegetation types are derived in the model from the values for the reference crop by converting with known crop factors (Feddes, 1987). The paved part of the urban area is assumed to have no evaporation, while the unpaved part is considered as grass.

Snow accumulation has been accounted for in the model: it is assumed that snow accumulation and snow melt are related to the daily average temperature. When the temperature is below 0 °C, precipitation falls as snow and accumulates. At temperatures between 0 °C and 1 °C, both precipitation and snow melt occur: it is assumed that during daylight hours the precipitation falls as rain, whereas precipitation falling during the night accumulates as snow (and the melt rate is 1.5 mm water per day). When the temperature is above 1 °C, the snow melts at a rate of 3 mm/day per degree Celsius.
For the temperature of a nodal point the temperature given for a region in the meteorological input file is corrected for the difference in ground level elevation, using a factor of 0.6 degree Celsius per 100 m. This constant was further differentiated to vary over the year, between 0.4 and 0.6 (Holko, personal communication).

2.3 Surface water flow

The surface water system in the Netherlands is often a dense network of watercourses. It is not feasible to explicitly account for all these watercourses in a regional simulation model, yet the water levels in the smaller watercourses are important for estimating the amount of drainage or subsurface irrigation, and the water flow in the major watercourses is important for the flow routing. The solution is to model the surface water system as a network of reservoirs. The inflow of one reservoir may be the discharge of the various watercourses and ditches, runoff and water from a sewage treatment plant. The outflow from one reservoir is the inflow to the next reservoir. The water level depends on surface water storage and on reservoir inflow and discharge. For each reservoir, input data are required on a 'stage versus storage' relation and a 'stage versus discharge' relation.

Watercourses are important for the interaction between surface water and groundwater. In the model, four different categories of drainage ditches (related to its size) are used to simulate are used to simulate the interaction between surface water and groundwater. The interaction is calculated for each drainage subsystem using a drainage resistance and the difference in level between groundwater and surface water (Ernst, 1978).

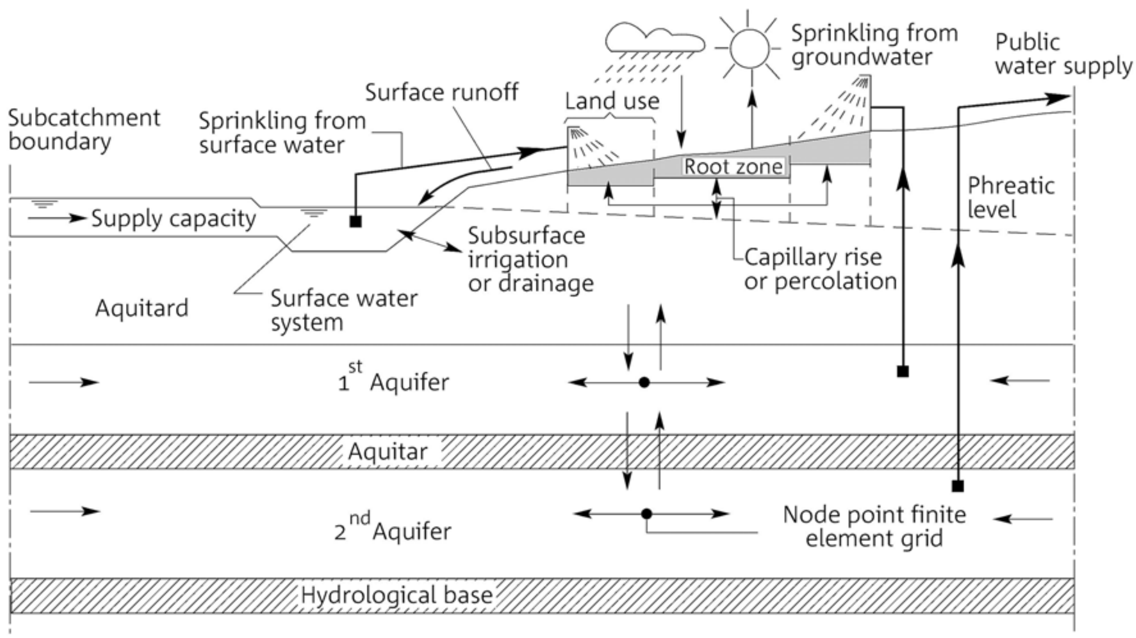

Figure 2.1
Schematisation of water flows in the SIMGRO model. The main feature of this model is the integration of saturated zone, unsaturated zone and the surface water systems within a sub catchment (Querner, 1997)

2.4 Linkage of groundwater–surface water modules

As the groundwater part reacts much more slowly to changes than the surface water part, both parts have their own time step. The result is that the surface water module performs several time steps during one time step of the groundwater module. The groundwater level is assumed to remain constant during that time and the flow between groundwater and surface water is accumulated using the updated surface water level. The next time the groundwater module is called up the accumulated drainage or subsurface irrigation is used to calculate a new groundwater level.

2.5 User interface AlterrAqua

AlterrAqua is a user interface in ArcView, developed around the SIMGRO model. The purpose of this application is to make the SIMGRO regional groundwater model more user-friendly and easy accessible. The application enables the use of SIMGRO within the GIS environment of ArcView. The power of the instrument is its link to existing digital geographical information (soil maps, land use maps, watercourses, etc.). SIMGRO inputs are generated in separate AlterrAqua modules. For more information and detailed description of SIMGRO input and output files, please refer to Dik (2005). For more information on the theory of SIMGRO, readers are referred to Van Walsum et al. (2004). For an example of the use of SIMGRO, readers are referred to Povilaitis et al. (2006). In this last study a SIMGRO model is used to analyze water management measures.

3 Methods to characterize droughts

3.1 Drought

A drought is defined as: *'a sustained and regionally extensive occurrence of below average natural water availability, and can thus be characterized as a deviation from normal conditions of variables such as precipitation, soil moisture, groundwater and streamflow'* (Tallaksen and Van Lanen, 2004). In this study the so-called threshold level method will be used to identify and characterize droughts.

3.2 Threshold level method

The threshold level method is the most frequently used method to define a drought (Tallaksen and Van Lanen, 2004), if the duration is required. It is based on defining a threshold, Q_z. Below this threshold the system is considered to be in a drought. Thresholds can identify droughts in different hydrological variables, such as river flows, groundwater levels, precipitation amounts and groundwater recharge.

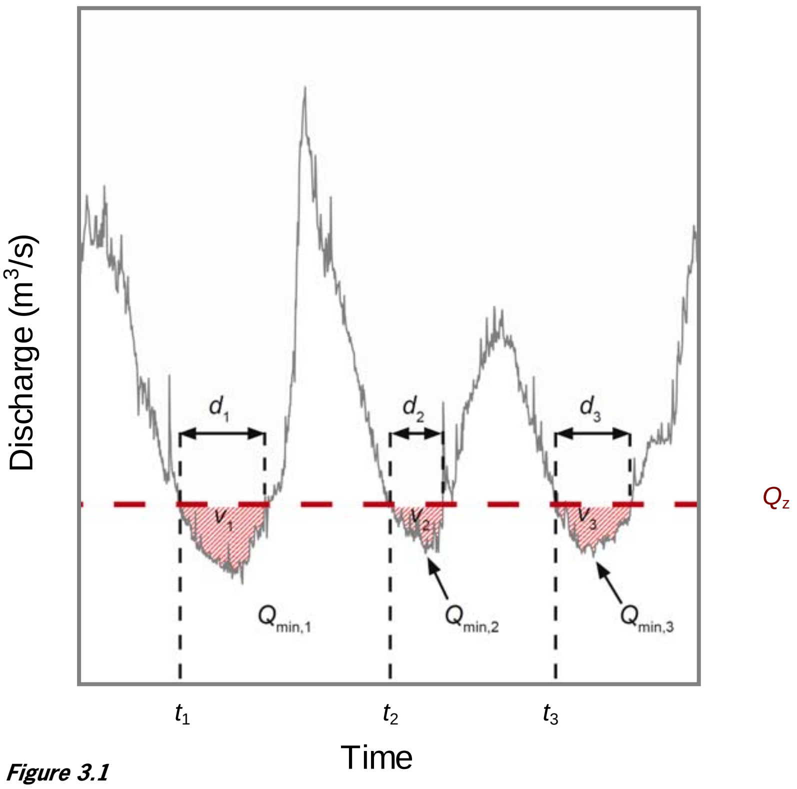

Figure 3.1
Example of drought characteristics defined with the fixed threshold method for a river flow (Fleig et al., 2006)

Figure 3.1 is an example on how the fixed threshold level method can be used to identify droughts. The fixed threshold method means that the threshold is constant throughout the whole year. A drought starts when the discharge or another hydro(meteo)logical variable drops underneath the threshold value, the drought stops when the discharge comes back above the threshold value.

With the help of this threshold approach it is possible to define the following drought characteristics shown in Figure 3.1:

- start of a drought (t_1);
- end of a drought;
- drought duration (d_i);
- severity of a drought (v_i).

3.3 Choosing a threshold value

The magnitude of a threshold changes with the type of river and the objective of the study. Studies that focus on aquatic ecosystem, for example, will have another threshold value than studies that focus on river flows for navigation. For perennial rivers, which have continuous flow, relatively low thresholds in the range from Q_{70} to Q_{95} can be considered as reasonable. For ephemeral rivers, which flow for very short periods, a threshold of Q_{70} may be zero. In such a case a higher threshold (e.g. Q_{20}) or a variable threshold may be used (Tallaksen and Van Lanen, 2004). The selection of the magnitude of the threshold used for this study will be described in Section 6.2.3.

3.4 Space-time development of droughts

The severity of a drought does not only depend on the length of a drought, but depends even more on the area in drought and the deficit over that area (Tallaksen et al., 2009). With the help of GIS the development of both the duration and the severity of an area in drought can efficiently be analyzed. By analyzing spatially distributed river basin characteristics, the area in drought and the deficit over that area can be linked to these characteristics of a drought event to investigate relationships. For an example of the use of spatial analyses of droughts, readers are referred to Rhebergen (2009).

4 Description of research area and model input

4.1 Introduction

The Rhine basin (Figure 4.1) has an area of 185,000 km^2 and receives water from nine different countries: Italy, Switzerland, Austria, Liechtenstein, Germany, France, Luxembourg, Belgium, and The Netherlands. The Rhine originates in the Swiss Alps, it has a length of 1,232 km, and it flows in the Netherlands into the North Sea. Along its way the Rhine receives water from several tributaries, such as: Ruhr, Moselle, Main, Neckar, Nahe and Aare. The highest point in the basin is the Finsteraarhorn mountain (Switzerland) with 4,274 m and the lowest point can be found near Nieuwerkerk aan den IJssel (The Netherlands) at 7 m below sea level.

After the river enters The Netherlands it bifurcates into several branches, because of that only the part of the catchment upstream of Lobith is studied (for the location of Lobith see Figure. 4.4). The part upstream of Lobith has an area of approximately 160.000 km^2.

For the SIMGRO model the groundwater system needs to be schematized by means of a finite element network. The network comprises of 8144 nodes spaced about 5 km apart and each node has an influence area of about 25 km^2.

Figure 4.1
Topographical map of the Rhine basin (Unep Grid Europe, 2005).

4.2 Surface water

4.2.1 Description

The Rhine can be characterized as a rain-fed/melt water river. This is likely to shift in the 21st century into a mainly rain-fed river as a consequence of the changing climate (Pfister at al., 2004). In Figure 4.2 the average discharge of the Rhine at the German-Dutch border (Lobith) is shown. The monthly average discharge varies between 1500 and 3000 m^3/s. The yearly average discharge is 2247 m^3/s (Figure 4.2).

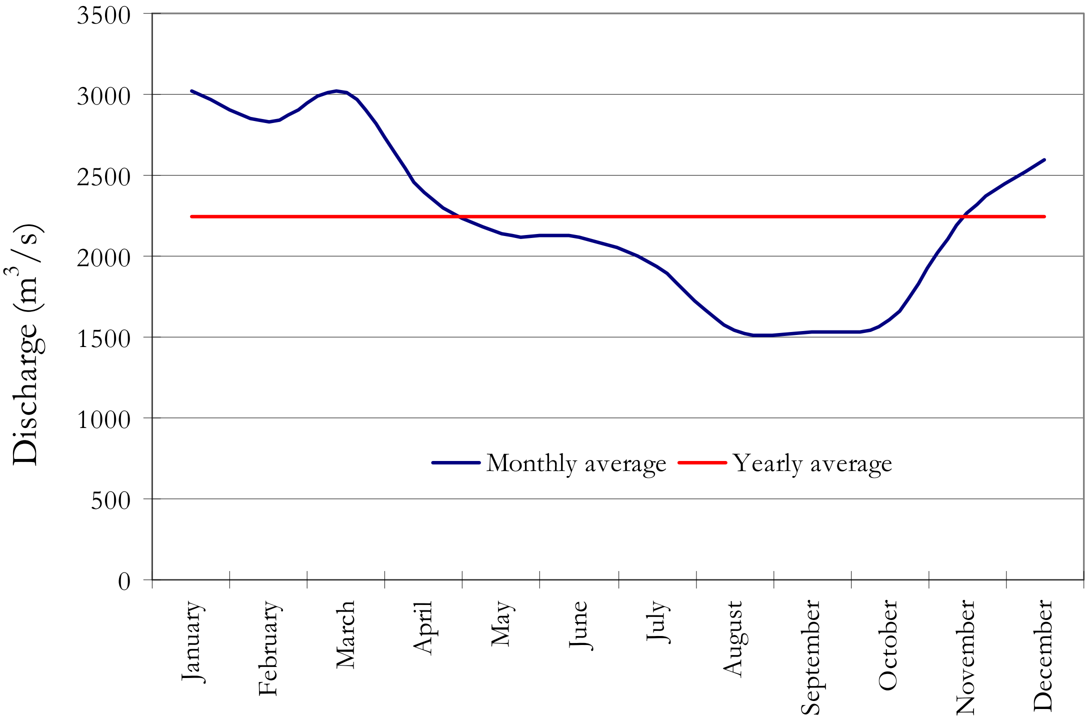

Figure 4.2
Monthly and yearly average discharge of the Rhine at Lobith; period 1989-2003 (data source: CHR).

To examine the contribution of the Swiss part of the basin upstream of Rheinfelden (for gauge Rheinfelden see Figure 4.4) to the total discharge at Lobith, the discharges of both points can be compared. In Figure 4.3 the daily discharges are compared from the most downstream gauging station in Switzerland (Rheinfelden) to the daily discharges at Lobith. From this figure it becomes clear that the Swizz part of the basin (around 23% of the total research area) accounts on average for more then 50% of the discharge at Lobith. The reason for this is the high precipitation amounts in the Alps relative to the rest of the basin. At certain moments the discharge exceeds the 100%, this means that the discharge at Rheinfelden is at that moment higher than the discharge at Lobith. The peak of a peak flow recorded at Rheinfelden, takes some time (3 to 5 days) to reach Lobith.

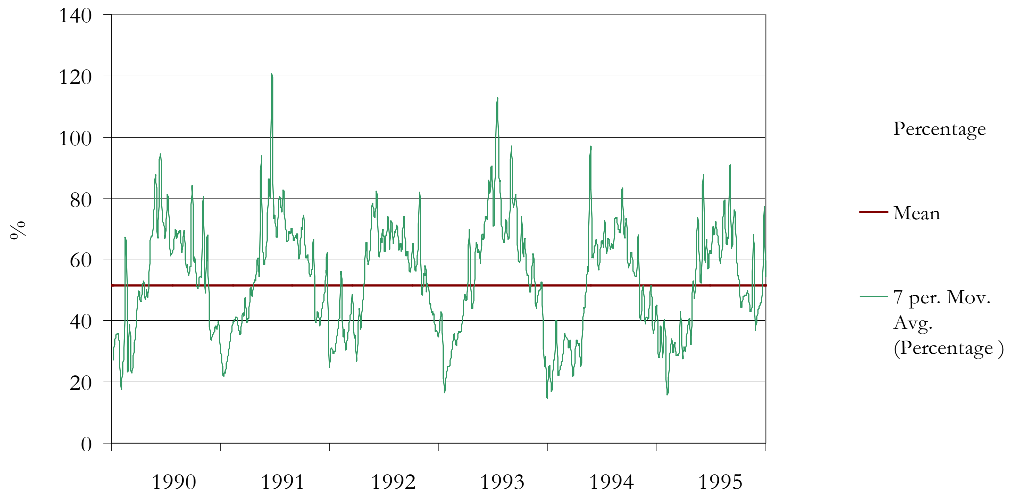

Figure 4.3
Percentage of the discharges at Rheinfelden versus Lobith as a 7 day moving average.

The Rhine has been modified drastically by human activities in the past. Prior to the 19th century the Rhine was a multi-channel system with upstream of Mannheim a braided system (network of small channels separated by small and often temporary, gravely islands) and downstream from Mannheim the Rhine was a meandering river. In the 19th and 20th century the river was regulated and straightened. This straightening of the river resulted in a much shorter river, e.g. between Basel and Mannheim the length reduced from 354 km to 273 km (Silva et al., 2001).

4.2.2 Model input

The drainage network has been incorporated in GIS by Vogt et al. (2007) and used for the interaction groundwater surface water in the SIMGRO model. For the flow direction and linkage of the sub-catchments that data has been simplified by removing the streams with a drainage area smaller than 400 km^2. The result of this simplification can be found in Figure 4.4. The gauging stations used to compare the simulated and measured discharges are presented as well in Figure 4.4. There was data available for 42 gauging stations, for most of them from 1985 till 1995.

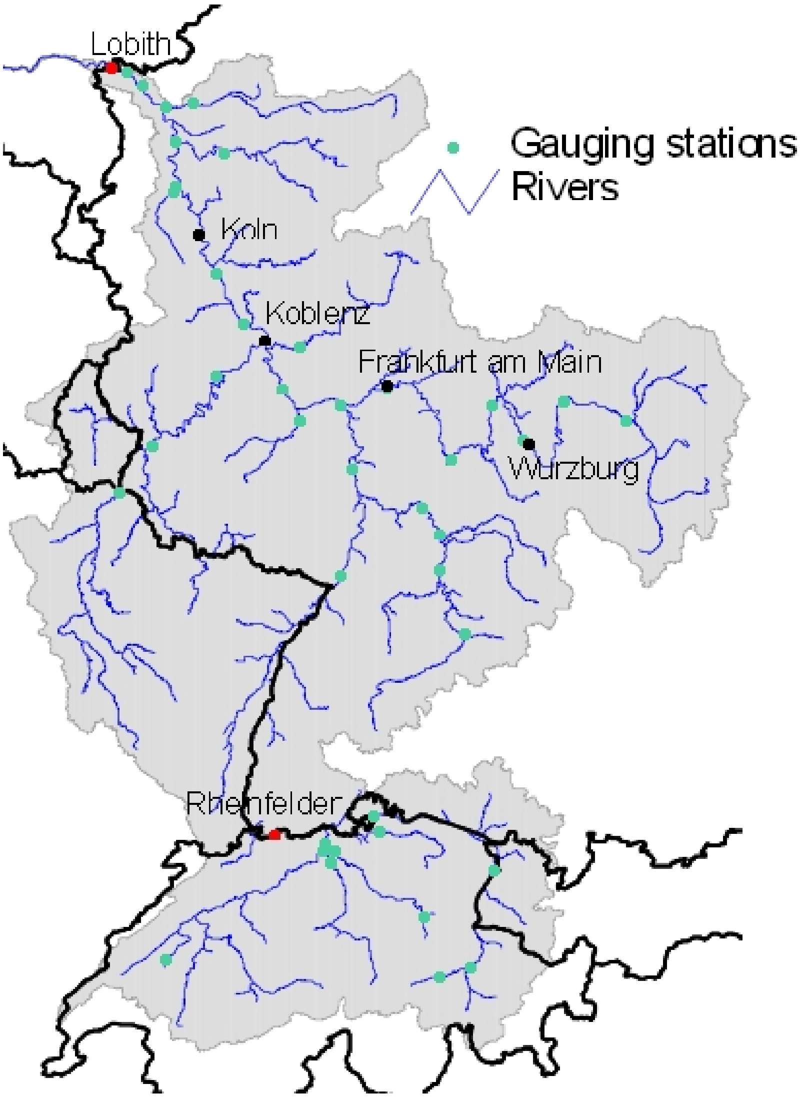

Figure 4.4
The major streams and the gauging stations in the Rhine basin.

As previously described in Chapter 2, SIMGRO uses sub-catchments to perform the calculations for the surface water. Figure 4.5 shows the 630 sub-catchments which represent the surface water system for the Rhine basin.

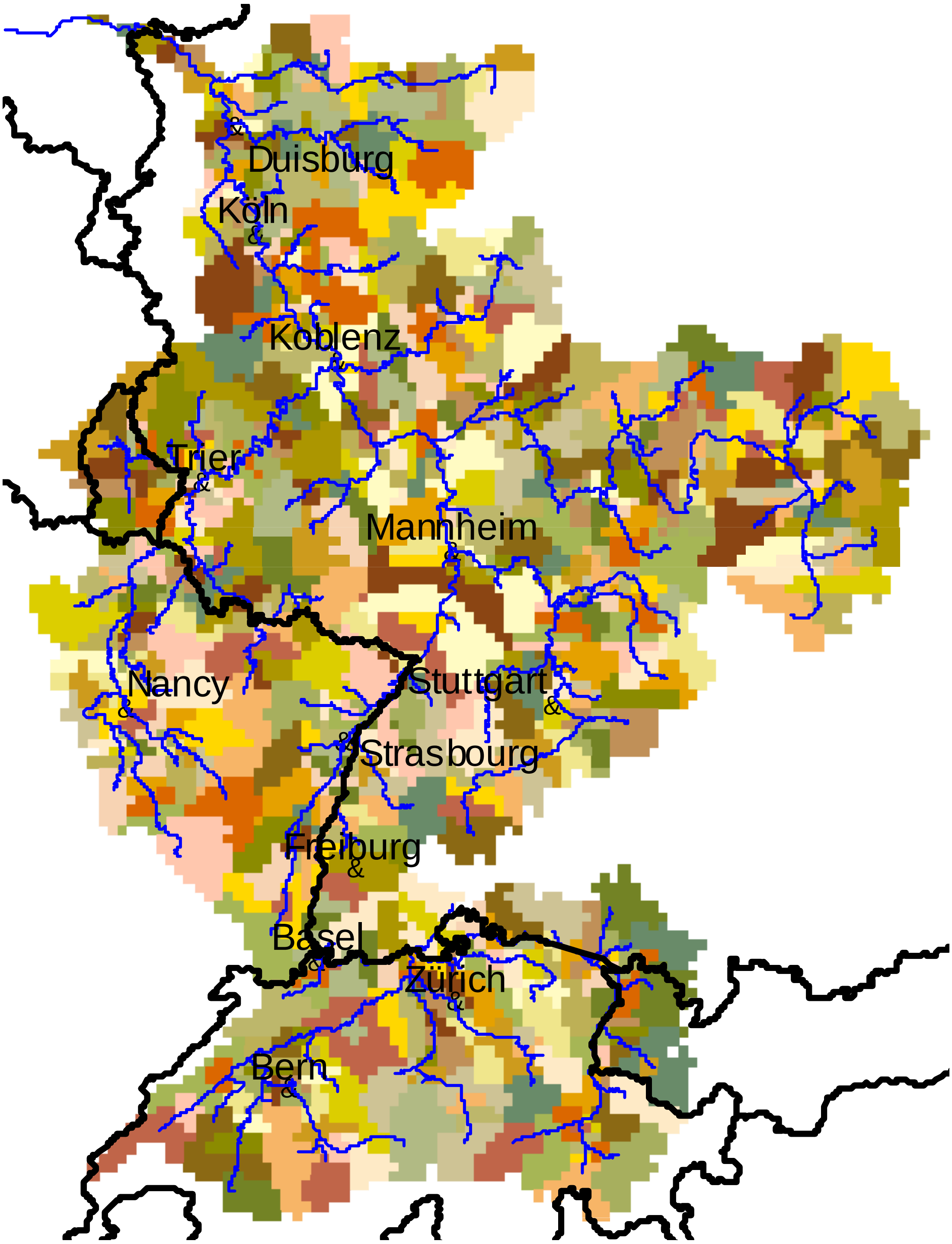

Figure 4.5
Sub-catchments, used by SIMGRO to perform the calculations for the surface water system.

4.3 Soils

4.3.1 Unsaturated zone

Because of the diversity in soils in the Rhine basin only a general description is given in this report. For a more thorough description of the soils in the Rhine basin, readers are referred to CHR (1978). The available soil classification is based on the World Soil Classification of the FAO (1974). In the high Alps, Lithosols are the main soil type. When we look at the lower mountain ranges, such as the Vosges and the Black Forest, the dominant soil type are Cambisols. In the flood plains along the Rhine mainly Fluvisols can be found. In the lower Rhine area (downstream from Cologne), Podsols are the dominant soil type.

For the unsaturated zone the soil-water characteristics has been derived using the hydrologeological map of the Rhine basin (CHR, 1978) together with expert judgment. The soil-water characteristics, as a function of the depth of the groundwater, were selected from sandy and sandy to loam soils. This resulted in eight different types, representing a low to high moisture contents for the root zone (column *types*). The values correspond to the data shown in Table 4.1 (column *Sy (unsaturated)*). This data was used as input to the SIMGRO model of the Rhine basin.

4.3.2 Saturated zone

For the saturated zone, SIMGRO needs the transmissivity of the subsurface (kD) to simulate the flow in the aquifers and the aquitards. When the input data was collected the choice has been made to use a single aquifer. The kD values used as input for the model were determined with expert judgment and the help of a hydrogeological map of the Rhine basin (CHR, 1978). This map differentiates geohydrological units for the Rhine basin. This resulted in the kD values that can be found in Table 4.1 and is spatially presented in Figure 4.6. In Table 4.1 a number of hydrogeological units were left out because they were not relevant for the study area. The kD values range from 3 to 6000 m^2/d. Hollis et al. (2002) provide a dataset with measured kD values in the Rhine basin, which correspond well with the ranges in kD values shown in Figure 4.6. For the storage coefficient at the phreatic surface for a depth of 10 m and more the values are shown in Table 4.1 (column *Sy (saturated)*).

Table 4.1
kD values and Sy values for the Rhine basin

Name	kD (m^2/day)	Sy (unsaturated)	Sy (at 10 m depth)	Types
I Groundwater in porous rocks				
1. Gravelly to sandy fluviatile (or fluviaglacial) deposit; partly cover by low conductivity toplayer	5000	0.3	0.3	1
2. Fine to coarse sand (partly compacted)	1000	0.25	0.25	1
5. Volcanic tuff, unconsolidated to slightly consolidated	50	0.25	0.15	4
II Groundwater in fractured hard rock, incl. karstified rocks				
6. Sandstones (fractured and porous), and Conglomerates with unorganized shale layers	250	0.2	0.2	3
7. Limestones, Dolomites and Marls, beds, fractured and karstified (incl. Helvetikum)	100	0.1	0.025	8
8. Limestones and Dolomites, often intermediately to strongly karstified	100	0.1	0.05	7
9. Basalt, thick flows, strongly fractured	250	0.1	0.025	8
11. Sequence of Limestone, Shale and Sandstone	50	0.1	0.025	8
12. Sequence of Marl and Shale with and dolomite, partly containing $CaSO_4$	5	0.1	0.025	8
13. Quartzite's and Sandstones with unorganized platy shale layers	50	0.15	0.025	8
14. Volcanic rocks, felsic to mafic, and associated tuffs	50	0.1	0.025	8
III Local groundwater (porous or fractured) or areas with not worth mentioning groundwater				
15. Moraine deposits (heterogeneous, marl, clay to gravel) and Loess	3	0.1	0.1	5
16. Clay, Marl, clayey Conglomerates, slightly consolidates fine-grained sandstones (some places with lignite)	5	0.075	0.025	8
17. Marl and Shale with Sandstones and Limestone layers (partly containing $CaSO_4$ and NaCl)	5	0.1	0.025	8
18. Sequence of Quartzite's, Sandstones and platy Shale	5	0.15	0.025	8
20. Granites and Granite-Gneiss (Central Alps)	50	0.075	0.025	8
21. Marl and Shale, platy, and Phylite (Bünder Schiefer)	3	0.05	0.025	8
22. Sequence of platy Shale, Sandstone, Quartzite and Grauwacke	5	0.1	0.025	8
23. Gneiss and Micaschist	3	0.075	0.025	8

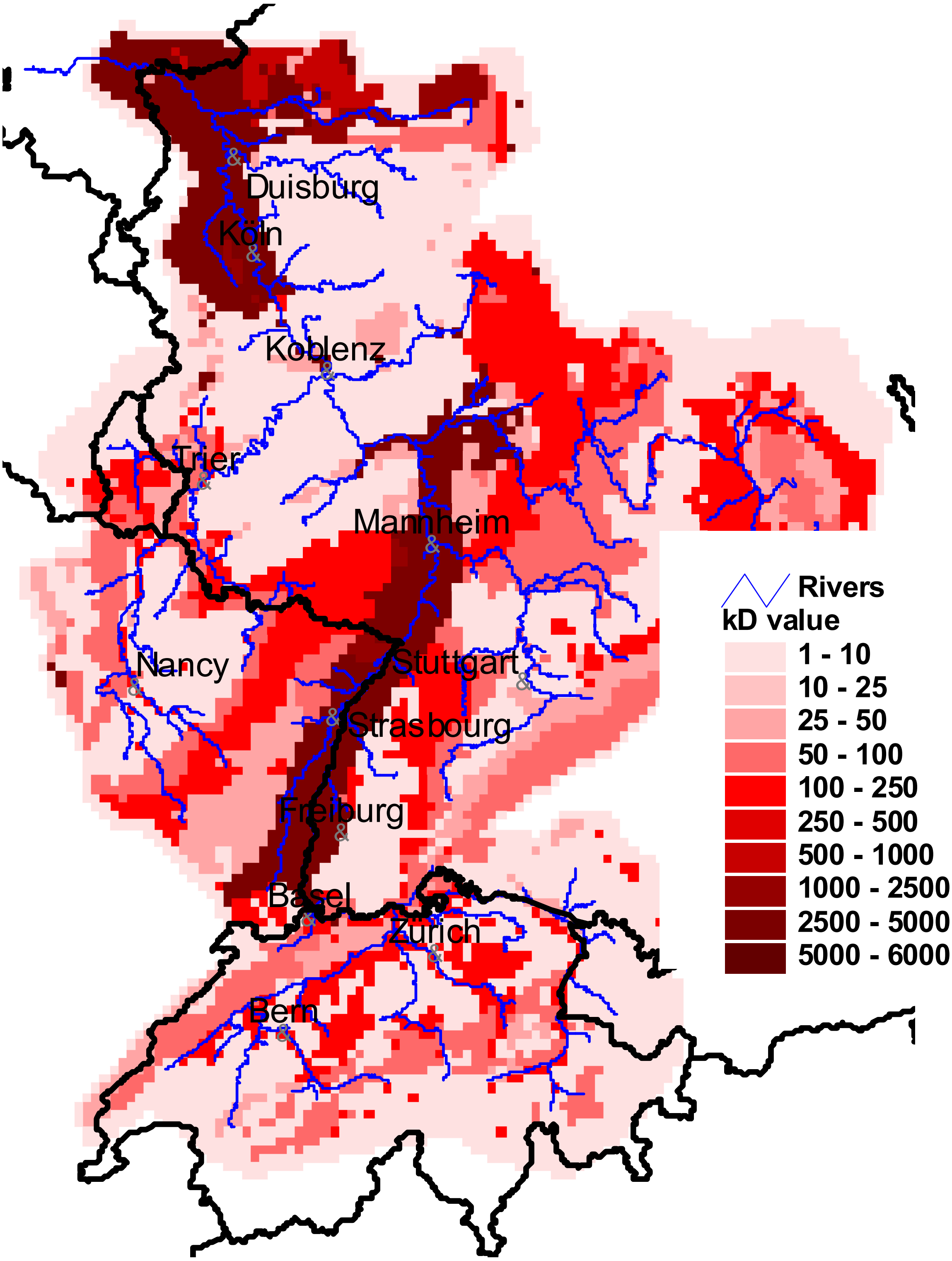

Figure 4.6
Transmissivity (kD in m²/day) for the Rhine basin.

4.4 Land use

4.4.1 Description

The Rhine basin is heavily industrialized and with an average population of 250 people per km^2 densely populated (Pinter et al., 2006). Human influences have had great consequences on the land use in the area. Table 4.2 gives an overview of the different types of land use and their proportion.

Table 4.2
Land use type and area covered (CORINE 2000 + Swiss Federal Statistical Office).

Land use type	%
Crops (mainly maize and grain)	33
Grassland	21
Deciduous forest	20
Pine forest	15
Urban	4
Other	7

4.4.2 Model input

The CORINE database contains land use maps for Europe based on satellite images. This map contains different land covers, divided into 44 different classes. This CORINE database only covers the EU-member states. For the Swizz part of the basin a map was used (which has the same legend as the CORINE maps) from the Swiss Federal Statistical Office. See also paragraph 5.1. The CORINE and Swiss land use data were simplified into twelve classes for the SIMGRO model. The map that was used as input for the model can be found in Figure 4.7.

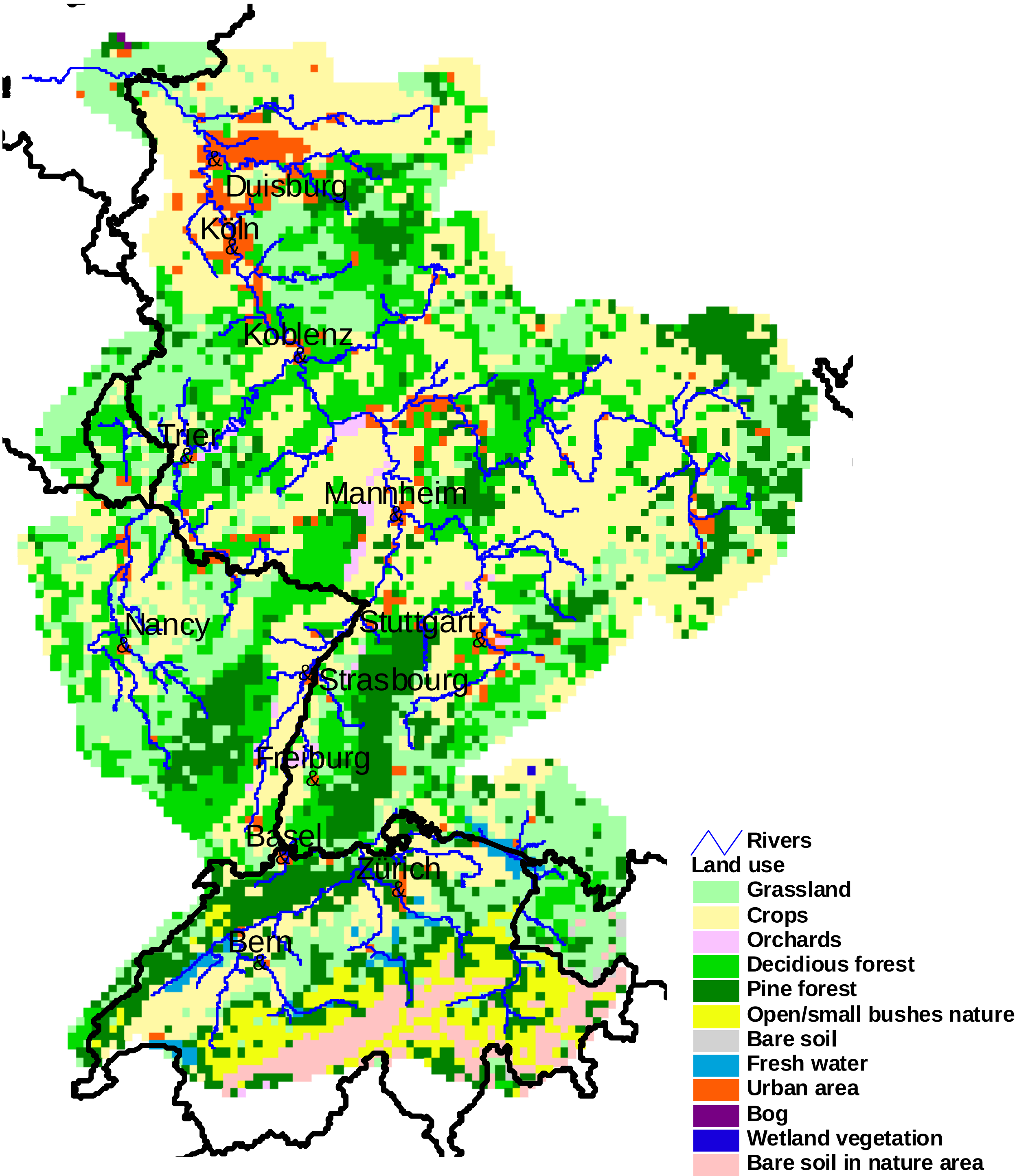

Figure 4.7
The differentiation of land use in the SIMGRO model.

4.5 Climate

4.5.1 Description

The Rhine basin is located in an area with temperate climatic conditions, characterized by frequent weather variations (Pfister et al., 2004). The yearly average precipitation shows large differences throughout the basin, from up to 2.000 mm in parts of the Alps, to 570 mm in parts of Germany.

4.5.2 Model input

The meteorological data that is needed by SIMGRO to carry out the calculations is precipitation and a potential evapotranspiration for a reference crop (e.g. grass cover). In this study precipitation and potential evapotranspiration data was used from 134 HBV-regions (Figure 4.8). These regions are meteorological regions and each nodal point is assigned to one of these regions. The data is available on a daily basis for the period 1961-1995. This data is received from the CHR (International Commission for the Hydrology of the Rhine basin).

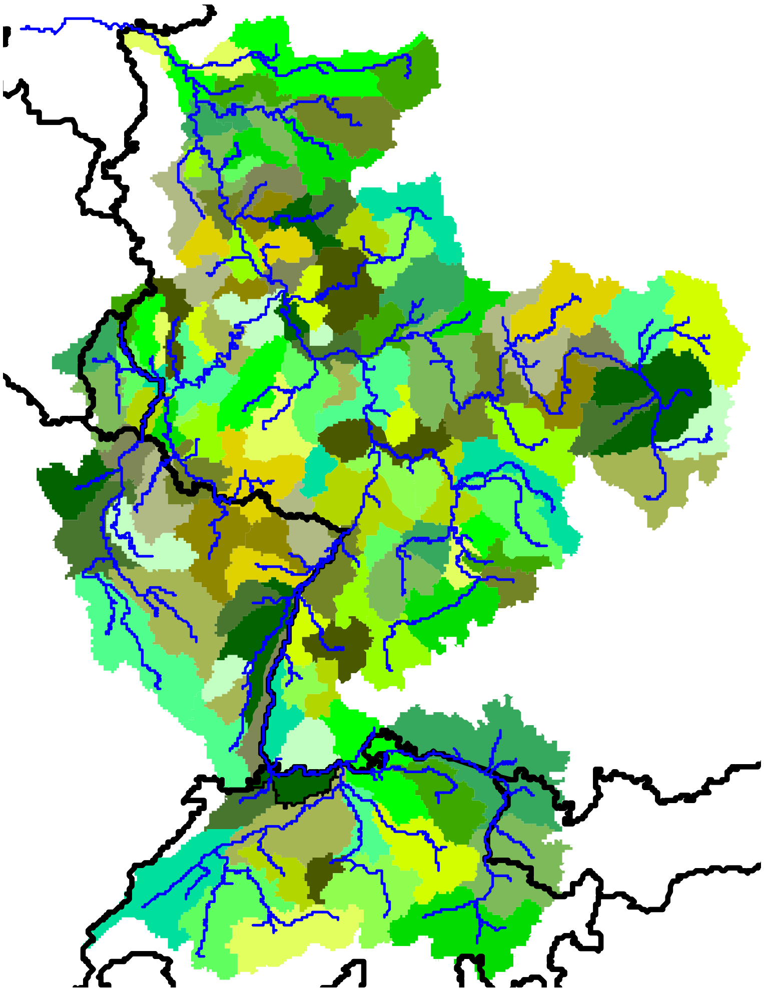

Figure 4.8
Rhine basin with sub-regions for the input of precipitation and potential evapotranspiration.

5 Improvements to the input data and model performance

The input data used for the SIMGRO model of the Rhine basin, has been based on the data used by Querner (2009). The improvements that were made to that data are described below. From this point forward the data that was used by Querner (2009) is referred to as 'original' model input data and the improved input data made in this thesis is referred to as 'final' model input data.

5.1 Improvements to the input data

The changes from the original input data to the final input data took place in several steps, which are described below.

In the first step towards the final input data the meteorological data is spatially distributed over 134 regions in the Rhine basin (Paragraph 4.5.2 and Figure 4.8). The 'original' version made use of meteorological data from De Bilt in the Netherlands.

In the original version the land use from the EU project CORINE was used as input, this was not available for Switzerland, because they are not a member of the European Union. Land use data from Switzerland was obtained from the Swiss Federal Statistical Institute and added to the input data of the model (Figure 4.7). In this step also the water levels in the lakes of Switzerland were adapted to the right level by adapting the level of weirs downstream of the lakes.

In the final step the transmissivity of the subsurface (kD) was spatially distributed (Figure 4.6). In the original version this kD value was 50 m^2/day as one aquifer for the whole basin. Furthermore the moisture content of the root zone was regionally differentiated in this step and added to the final data (see also Par. 4.3.1). The snow component was also included in the final step.

5.2 Model performance with new input data

For the presentation of the differences between measured and calculated discharge, the Nash-Sutcliffe modelling efficiency E has been used (Nash and Sutcliffe, 1970). Table 5.1 shows the different steps in model improvements, together with the resulting Nash-Sutcliffe modelling efficiency E . This efficiency figure shows how reliable the model simulates the real situation. The closer the model efficiency is to 1, the more accurate the model is. Values above 0.75 will be seen as acceptable in this study. An efficiency of lower than zero indicates that the average value of the measured time series would have been a better predictor than the simulations of the model (Krause et al., 2005). In Table 5.1 the second column from the left shows the performance of the Rhine model with the use of the original data. The utmost right column shows the performance with the use of the final data. Two intermediate steps show the improvement of the model using detailed meteorological data and land use/lake levels.

Table 5.1
Steps in the improvement towards the final model, with the Nash-Sutcliffe modelling efficiency E (for the period 1990-1995).

	'Original' data	New meteo data	Land use + lakes	'Final' data
Lobith	0.26	0.85	0.84	0.89
Main	-1.12	0.82	0.82	0.76
Neckar	-0.16	0.77	0.77	0.79
Moselle	0.51	0.87	0.87	0.80
Rhine upstream of Basel (average of five stations)	-2.33	-1.62	-1.63	0.25
Rhine downstream of Basel (average of thirteen stations)	-0.14	0.74	0.73	0.88
Average of the six values above	-0.50	0.41	0.40	0.73

The performances of the Rhine model with the final data shows considerably better results than the model with the original data. Especially Lobith has a Nash-Sutcliffe *E* of 0.89, which can be considered as a very good result. In Figure 5.1 the measured discharge is given with the simulated discharges of the three crucial steps in development (*original*, *new-meteo* and *final-data*). *Land use + lakes* is not included to the figure because of the large similarities to the *new meteo data*. Low discharges are simulated very well with the final data. Only the peak discharges are simulated too low. From Figure 5.1 and from Table 5.1 it becomes clear that the new meteo data caused the largest improvement to the performance of the Rhine model. The Nash-Sutcliffe modelling efficiency *E* of the river flow upstream of Basel is fairly good with 0.25. However, it improved substantially from -2.33 for the original data. The average *E* shows for almost each step an improvement, from the original data with -0.50 to the final data with 0.73. Note that the model performs less good in the Main and Moselle basins with the spatial differentiation of the kD values and the moisture content of the root zone (final data). However the average *E* still shows a clear improvement to the performances of the model with the use of this 'final' input data.

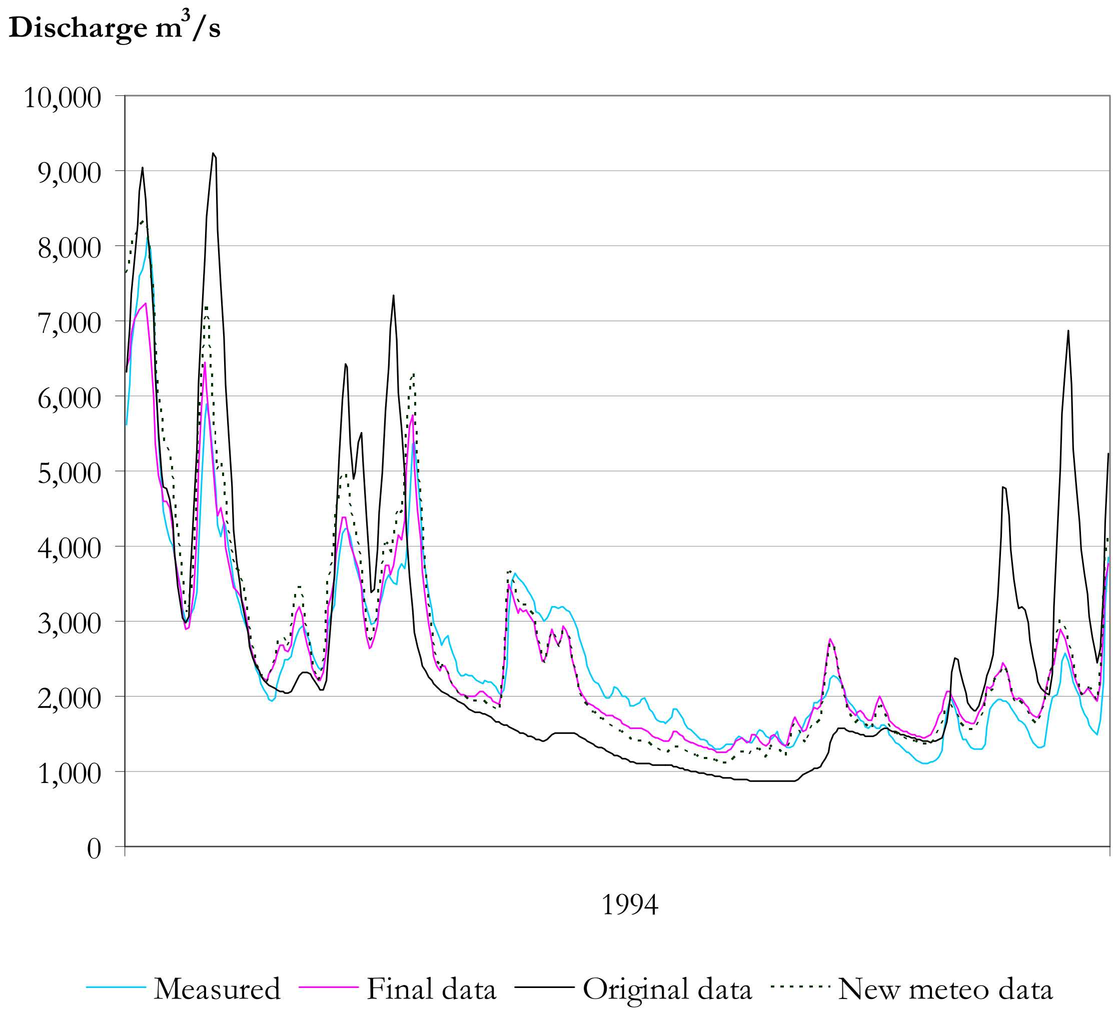

Figure 5.1
Simulated and measured discharge at Lobith for 1994.

To show the performances of the model with the final data, Table 5.2 has been added. In this table you can find, for each of the 42 gauging stations the average discharge measured, simulated, the difference between measured and simulated, and the *E*. From this table we can see that for 38 of the 42 gauging stations the *E* is between 0 and 1. Out of the remaining 4, there are 3 *E* values between 0 and -0.5, and one with -5.11. The lowest *E* value of -5.11 is in a small tributary (average discharge of 11.2 m^3/s) of the Rhine near Düsseldorf (Germany). In the basin of this tributary (Erft) are large open-pit mines (for lignite), for this open-pit mining it is necessary to artificially lower the groundwater table, and this could explain the high differences between simulated and measured discharges.

Table 5.2
Differences between calculated and measured discharges and the Nash-Sutcliffe model efficiency for the period 1990-1995.

Gauging station	AVMS[1] (m^3/s)	AVCL[2] (m^3/s)	DDAV[3] (m^3/s)	E (Nash-Sutcliffe)
Andelfingen	45.5	37.3	-8.2	0.19
Andernach	2033.9	2044.6	10.7	0.90
Baden	89.0	63.6	-25.4	-0.16
Bonn	2004.4	2031.0	26.6	0.90
Brugg	313.1	265.2	-47.9	0.49
Cochem	327.2	326.3	-0.9	0.80
Diepoldsau	186.3	150.4	-35.9	0.51
Domuth-Ems	124.1	111.9	-12.2	0.51
Dusseldorf	2136.8	2138.9	2.1	0.91
Emmerich	2207.2	2333.6	126.4	0.90
Grolsheim	26.6	35.6	9.1	0.70
Gundelsheim	90.2	149.0	58.7	0.52
Hattingen	72.4	79.8	7.4	0.90
Iilanz	36.9	45.8	9.0	0.13
Kalkofen	47.6	52.6	5.0	0.75
Kaub	1661.1	1643.5	-17.7	0.88
Kleinheubach	2100.0	2113.4	13.4	0.90
Koln	154.5	201.1	46.6	0.76
Lauffen (am Neckar)	66.9	95.0	28.1	0.65
Linth	34.4	23.4	-11.0	0.31
Lobith	2160.1	2353.0	192.9	0.89
Mainz	1564.4	1562.7	-1.7	0.86
Maxau	1242.8	1096.0	-146.9	0.76
Mellingen	122.3	104.6	-17.7	0.45
Neubruck-Erft	11.2	15.2	4.1	-5.11
Neuhausen	301.0	236.4	-64.6	-0.23
Payerne	8.8	10.3	1.5	0.52
Perl	144.4	133.1	-11.3	0.74
Plochingen	45.1	52.7	7.6	0.64
Rees	2198.6	2331.9	133.3	0.91
Rheinfelden	927.8	766.3	-161.5	0.34
Rockenau	133.6	153.5	19.9	0.79
Ruhrort	2218.7	2233.4	14.8	0.92
Schermbeck	32.3	61.5	29.2	-0.27
Schweinfurt	120.3	119.2	-1.0	0.73
Steinbach	133.0	171.1	38.1	0.76
Stilli	527.6	435.5	-92.1	0.39
Trier	273.0	290.4	17.3	0.83
Trunstadt	112.9	110.7	-2.2	0.74
Wesel	2215.5	2247.0	31.5	0.91
Worms	1392.8	1303.8	-88.9	0.81
Wurzburg	111.8	130.7	19.0	0.71

[1] Average measured
[2] Average simulated
[3] Difference between average simulated and measured[3] Average measured
[3] Average simulated
[3] Difference between average simulated and measured

6 Scenarios

6.1 Introduction

In this chapter, two scenarios are introduced and the effect of the scenarios on the discharges and droughts in the Rhine basin are presented. The two scenarios include climate change and land use change. The reference situation, were the different scenarios are compared to, is the model that uses the final input data (Chapter 5).

6.2 Climate change

The climate is changing on a global scale (IPCC, 2007). In the Rhine basin, impact of climate change has been reported by numerous authors (Pfister et al., 2004; Middelkoop et al., 2001; Hurkmans, 2009). How fast the climate is going to change and to what degree is not certain. Different climatic models give different outcomes. For Western Europe all the models point to the same direction:

- Temperatures will continue to rise. Hot summers and mild winters will become more common;
- Winters will become wetter and extreme precipitation will increase;
- The number of rainy days will decrease in summer, but rain showers will intensify;
- The sea level will continue to rise.

To summarize and specify the outcomes from the different climatic models the KNMI (Royal Dutch Meteorological Institute) developed a number of scenarios (Van den Hurk et al., 2006). The scenarios represent changes in temperature, precipitation, wind, and sea level for the climate in 2050 relative to 1990. Please note that these scenarios have been developed for the Netherlands and not for the whole Rhine basin. However, we assume that these scenarios are also applicable to the whole Rhine basin.

The KNMI analyzed the results from a large number of climatic models and combined these with observed series, which finally resulted into climate scenarios. The outcome from the climatic models differs considerably from each other, because our understanding of the complex processes in the climatic system is still limited. The uncertainty increases even more when zoomed in from a global scale to a regional scale, such as Western Europe. At the scale of Western Europe, air circulation plays an important role. Most of the models that were analyzed by the KNMI showed a clear change in circulation patterns above Western Europe. However, the magnitude and direction of change differ between models. To deal with these uncertainties, the KNMI defined four climate scenarios from a range of possible future directions. Each of the four scenarios are possible, but with the current knowledge it is impossible to say which scenario is most plausible. The four scenarios, presented by the KNMI, are:

- G, Moderate, 1 °C temperature rise on earth in 2050 compared to 1990, no change in air circulation patterns in Western Europe;
- G+, Moderate, 1 °C temperature rise on earth in 2050 compared to 1990, + milder and wetter winters due to more westerly winds, + warmer and drier summers due to more easterly winds;
- W, Warm, 2 °C temperature rise on earth in 2050 compared to 1990, no change in air circulation patterns in Western Europe;
- W+, Warm, 2 °C temperature rise on earth in 2050 compared to 1990, + milder and wetter winters due to more westerly winds, + warmer and drier summers due to more easterly winds.

The change in meteorological variables associated with these scenarios are listed in Table 6.1 (Van den Hurk et al., 2006). For more information on the KNMI'06 climatic scenarios, readers are referred to Van den Hurk et al. (2006).

Not all the four KNMI'06 scenarios were used in our study to investigate the impact on the river discharges and droughts in the Rhine basin. Table 6.1 illustrates that the precipitation increases in summer for the G and W scenarios. In this study the focus is on drought that is why the G+ and W+ scenarios were used, where there is a decrease in summer precipitation, respectively 10% and 19%. This means that we focus on a changing climate with a change in air circulation patterns in Western Europe and it is expected that these two scenarios will result in lower discharges in summer and a the maximum possible increase in droughts.

Table 6.1
KNMI'06 climate scenarios for 2050 and the changes relative to 1990.

Scenarios	G	G+	W	W+
summertime values				
mean temperature (°C)	+0.9	+1.4	+1.7	+2.8
mean precipitation (%)	+3.0	-10.0	+6.0	-19.0
10 yr return level daily precipitation sum (%)	+13.0	+5.0	+27.0	+10.0
potential evaporation (%)	+3.0	+8.0	+7.0	+15.0
wintertime values				
mean temperature (°C)	+0.9	+1.1	+1.8	+2.3
mean precipitation (%)	+4.0	+7.0	+7.0	+14.0
10 yr return level daily precipitation sum (%)	+4.0	+6.0	+8.0	+12.0

6.2.1 Results

To approach the KNMI'06 scenarios, the precipitation and the potential evapotranspiration (Table 6.1) has been changed in the input of the model (delta change approach). In Table 6.2 the effects of the two selected KNMI'06 scenarios on the discharges are presented. Note that the mean yearly minimum discharges and the mean yearly maximum discharges is based on the minimum or maximum daily discharge in each of the six years.

G+ Scenario
Table 6.2 shows that the mean yearly minimum discharge decreases for the G+ scenario with minimal 4.9% (Moselle) up to as much as 14.3% for the Neckar basin. The mean yearly maximum discharge does not show a clear decrease or increase. The Main and Neckar show a remarkable decrease in maximum discharge. This was unexpected with an increase of precipitation in winter of 7%. The mean discharge decreases at each gauging station for the G+ scenario, from 1.2% to 7.3%.

W+ Scenario
The mean yearly minimum discharge shows for the W+ scenario a large decrease between 7.2% (Moselle) and 22.9% in the Neckar basin. The mean yearly maximum discharge increases at each gauging station. The Main basin has the lowest change (+1.6%) and the Moselle basin the highest with +13.8%. The mean discharge

show for the W+ scenario a clear decrease, except for the Moselle basin, which remains more or less equal with a decrease of 0.1%.
The different tributaries of the Rhine react differently on the changes in climate, which can be caused by differences in storage across the sub-basins triggered by elevation differences, the groundwater system (transmissivity and storage) and the interaction between groundwater and surface water.

Table 6.2
The influence of climate change on the extreme discharges and mean discharges for 1990-1995.

Gauging station	Mean Yearly Minimum discharge (%)		Mean Yearly Maximum discharge (%)		Mean discharge (%)	
	G+	W+	G+	W+	G+	W+
Lobith	-10.1	-16.7	2.0	6.2	-5.1	-7.6
Main (Kleinheubach)	-7.5	-11.1	-1.5	1.6	-3.5	-3.9
Neckar (Rockenau)	-14.3	-22.9	-1.0	2.0	-7.3	-10.4
Moselle (Cochem)	-4.9	-7.2	6.0	13.8	-1.2	-0.1
Rheinfelden	-13.1	-22.4	0.5	5.4	-4.3	-6.7
Worms	-11.4	-20.3	3.4	9.7	-7.0	-11.3

6.2.2 Discussion

Several studies have used the KNMI'06 climate scenarios to study the flow of the Rhine (e.g. Wit et al., 2007, Deltacommissie, 2008, Te Linde, 2007). These studies presented results as changes in the mean winter and summer discharge. In our study we focus on the mean yearly minimum and address maximum discharge However, the different studies are compared in this section to give an idea about the differences.

The Deltacommissie (2008) used the W+ scenario to examine the river flow in the Rhine basin in the future. They expect the peak discharge of the Rhine at Lobith to increase for the year 2050 with 3% to 19%. This compared to the increase in the mean yearly maximum discharges of 6.2% (W+) is in the same range. However the 19% increase seems high. The study expects a decrease in mean summer discharges at Lobith of 0 to 35% for the year 2050. Also this figure is in the same range compared to the decrease of 16.7% (W+) in mean yearly minimum discharges from this study. For the mean winter discharges at Lobith the Deltacommissie (2008) expects an increase of 5 to 15%. This study expected a 6.2 % increase of mean yearly maximum discharges, this figure comes within the range of 5 to 15%. Compared to this study the Deltacommissie (2008) seems to come to similar figures, but the increase of peak discharges of 19% seems high. It is difficult to compare the outcomes of this study to the outcomes of the study Wit et al. (2007). That study only shows a graph and does not provide values connected to those graphs. From Figure 6.1 (Wit et al., 2007) the low flows in summer are for G+ and W+ respectively 22 and 37 % lower. Our results show at Lobith for G+ a decrease of 10 % and for W+ a decrease of 17 % in low discharges. The trends are the same (both lower discharges in summer) but the predicted decrease is significantly more in Wit et al. (2007).

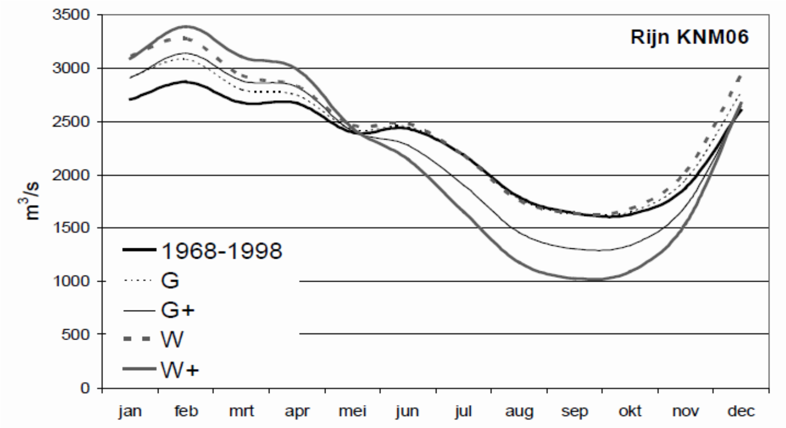

Figure 6.1
River discharges of the Rhine at Lobith with the KNMI'06 scenarios (De Wit et al. 2007).

Te Linde (2007) uses the W+ scenario with a HBV model of the Rhine basin to predict the change in river flow. In that study the flow at Lobith shows for the summer months a decrease in mean discharge of 42% and in winter an increase of 16%. These are considerable higher changes than derived in this study.

6.2.3 Effects on droughts

To study the effects of climate change (KNMI'06 scenarios) on droughts, the threshold value of Q_{90} for the flow at Lobith for the reference situation was introduced (Figure 6.2). The threshold value of Q_{90} equals a simulated flow by the SIMGRO model of 1265 m^3/s. The Dutch *Ministry of Transport, Public Works and Water Management* uses a variable value (monthly differentiated) of 1000 to 1400 m^3/s at Lobith to define whether the Rhine is in drought (V&W, 2010). This value is used by the Dutch government to warn users of the Rhine water for low flow conditions (navigation, power plants and water use for agriculture). The threshold value of Q_{90} (1265 m^3/s) is within the range of 1000 to 1400 m^3/s and is therefore considered to be reasonable to define droughts. From this point onward a threshold Q_{90} will be used to identify droughts in hydrological variables.

In Figure 6.2 the threshold value of Q_{90} has been included to the hydrograph for the reference scenario at Lobith. In this figure also the simulated discharges for the G+ and W+ scenarios have been added. The graph illustrates the effect of the climate scenarios on the discharge. In Table 6.3 the days in drought and the severity of the droughts have been given for the, reference, G+ and W+ scenarios. The reference situation has 220 days in drought for the period 1990-1995, being a discharge below the Q_{90} threshold of 1265 m^3/s. The number of days in drought increases by 117% to 477 days in the G+ scenario and to 653 days (+197%) in the W+ scenario. The severity of the droughts increases as well for the two scenarios. For the G+ scenario an increase of 181% is simulated and for the W+ by 406%. The number of droughts increases with the G+ scenario from 14 to 16, for the W+ scenario the number of drought decreases to 13, this is due to the merging of two droughts from the reference situation into one long drought.

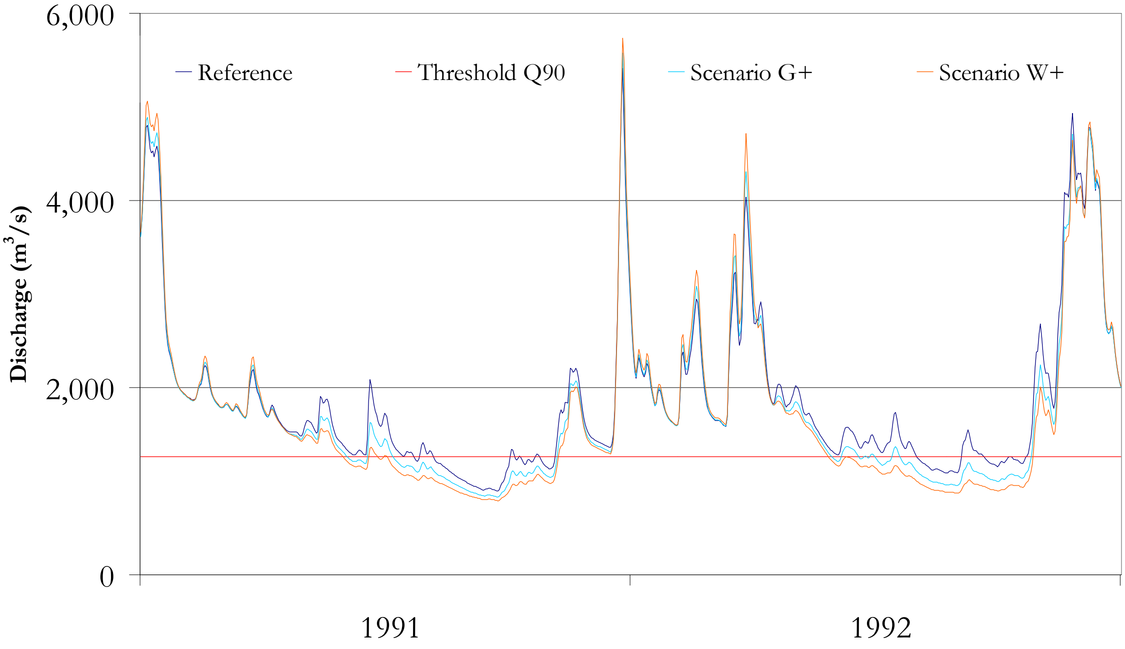

Figure 6.2
Discharges at Lobith for the reference situation together with the KNMI scenarios for the period 1991-1992.

Table 6.3
Drought analysis for the flow at Lobith for the period 1990-1995.

	Reference	G+	W+
Days in drought	220	447	653
Change in % from ref. situation		217 %	297 %
Severity of drought (m3)	2 175 x 106	6 118 x 106	11 010 x 106
Change in % from ref. situation		281 %	506 %
Number of droughts	14	16	13

6.3 Land use change

In this part the impact of land use change on the discharges and droughts in the Rhine basin will be investigated. This will be done by changing the land use types in the SIMGRO model.

The choice has been made to replace firstly all agricultural crops by grass and secondly all agricultural crops by forest (deciduous). By studying extreme changes in a single land use type (see Table 6.4) the maximum changes in the discharge within the basin can be examined. The approach was also carried out by Hurkmans (2009), using the VIC model.

In the input data for SIMGRO the land use was changed from agricultural crops to grass and from crops to deciduous forest. SIMGRO makes use of a different crop factor per land use type. The SIMGRO model uses crop factors in combination with a reference crop evaporation to calculate the potential evapotranspiration. This potential evapotranspiration gives in combination with the moisture content of the root zone the actual evapotranspiration. The crop factor of crop and grass are presented in Figure 6.3. For the agricultural crops a clear peak can be noted for the factor during the growing season, while grass has a more or less constant factor during the whole year. For forests the potential evapotranspiration is directly derived from the meteorological data rather than from the reference crop evaporation.

Table 6.4
Land use in the research area (Rhine basin upstream of Lobith) and the change.

Land use type	Current	Crop to grass	Crop to forest
Crops (mainly maize and grain)	3	0	0
Grassland	21	54	21
Deciduous forest	20	20	53
Pine forest	15	15	15
Urban	4	4	4
Other	7	7	7

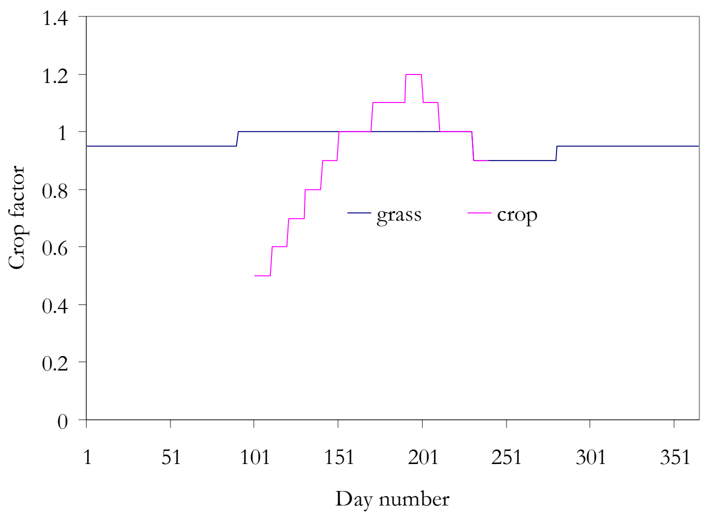

Figure 6.3
Crop factors for the land use type crop and grass.

6.3.1 Results

Table 6.5 presents the impact of the changes in land use on the discharge in the basin. The percentage of crop of the area in the reference situation is added to show how much of the area is affected by the land use change.

Cropland to grass
With the change from cropland to grass the effects in the mean yearly minimum discharges are minimal, showing all a minor decrease, with the biggest in the Neckar basin 2.8%. Like the mean yearly minimum discharges also the mean yearly maximum discharges show a decline throughout the whole Rhine basin, again the effects are minimal, with this time the Main basin as the most effected part with a decrease of 6.8%. Note that the Main basin is also the part with initially the highest percentage of cropland.

Cropland to forest
The change from crop to forest has a more clear effect on the discharges throughout the Rhine basin. Again the Neckar basin has the biggest change in the mean yearly minimum discharges of 10.5%. The outflow of the whole basin (Lobith) shows for the discharge a decline of on average 4%.

Table 6.5
The effects of the land use scenarios on the extreme discharges and mean discharge for 1990-1995.

Gauging station	**% of area is crop**	**Mean Yearly Minimum discharges (%)**		**Mean Yearly Maximum discharges (%)**		**Mean discharges (%)**	
		crop>grass	crop>forest	crop>grass	crop>forest	crop>grass	crop>forest
Lobith	33	-0.3	-4.1	-1.6	-3.3	-1.7	-4.0
Main (Kleinheubach)	52	-2.0	-9.4	-6.8	-10.5	-4.4	-7.9
Neckar (Rockenau)	40	-2.8	-10.5	-2.8	-5.8	-3.5	-7.8
Moselle (Cochem)	26	-0.9	-2.3	-1.7	-2.6	-1.8	-2.8
Rheinfelden	18	-0.4	-2.4	-1.5	-3.2	-0.9	-1.8
Worms	27	-0.7	-3.8	-1.1	-2.9	-1.2	-3.4

6.3.2 Discussion

In the study by Hurkmans (2009) the same land use types were changed. Therefore it is possible to compare the results. Hurkmans (2009) expects a decrease in discharges for both land use type changes as well. In Table 6.5 it is clear that the change to forest has a much bigger impact than the change to grass, in the study of Hurkmans (2009) this is also the case for the peak flows. However, for the minimum flows this is the other way around, in Hurkmans (2009) the change to grass has a bigger impact on the low flows than the change to forest.

To give an overview of all the different scenarios (G+, W+, *crop to grass* and *crop to forest*) Figure 6.4 has been added. Clearly, the W+ scenario shows the most extreme changes, as well as for the minimum and the maximum discharge. This is even better visible in Figure 6.5 where the different scenarios are presented relative to the reference situation.

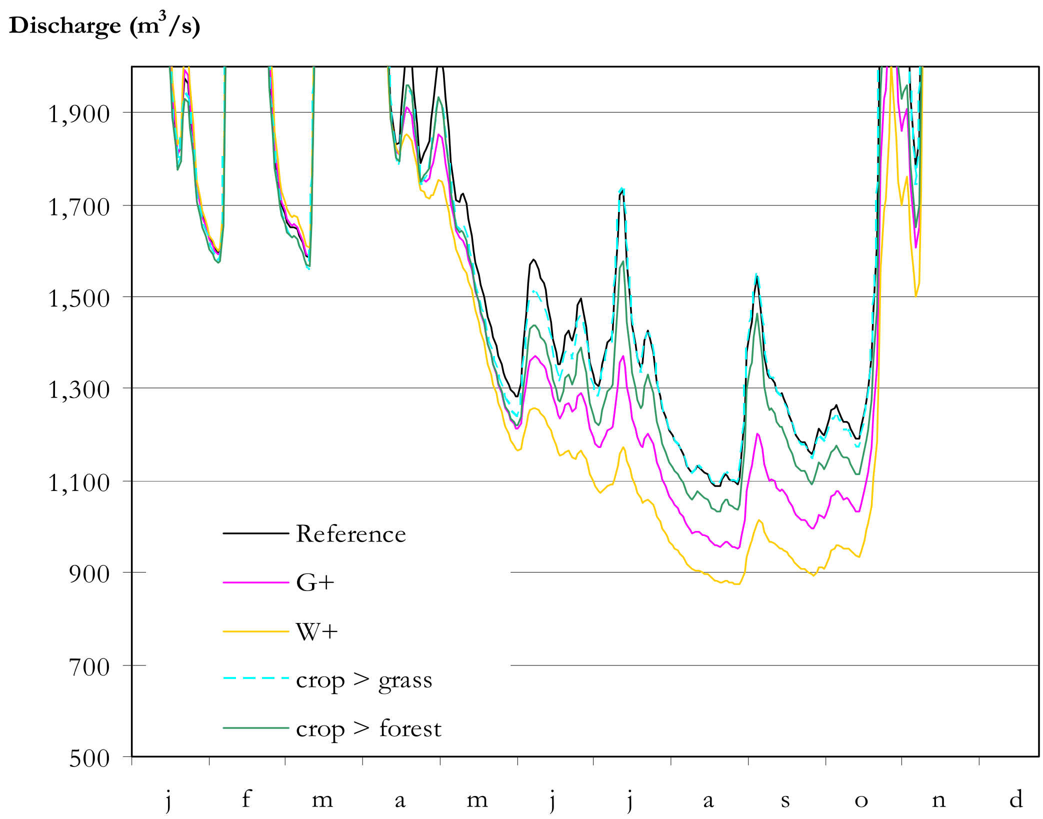

Figure 6.4
Daily flow at Lobith for the year 1992 for the different scenarios (with the focus on low discharges).

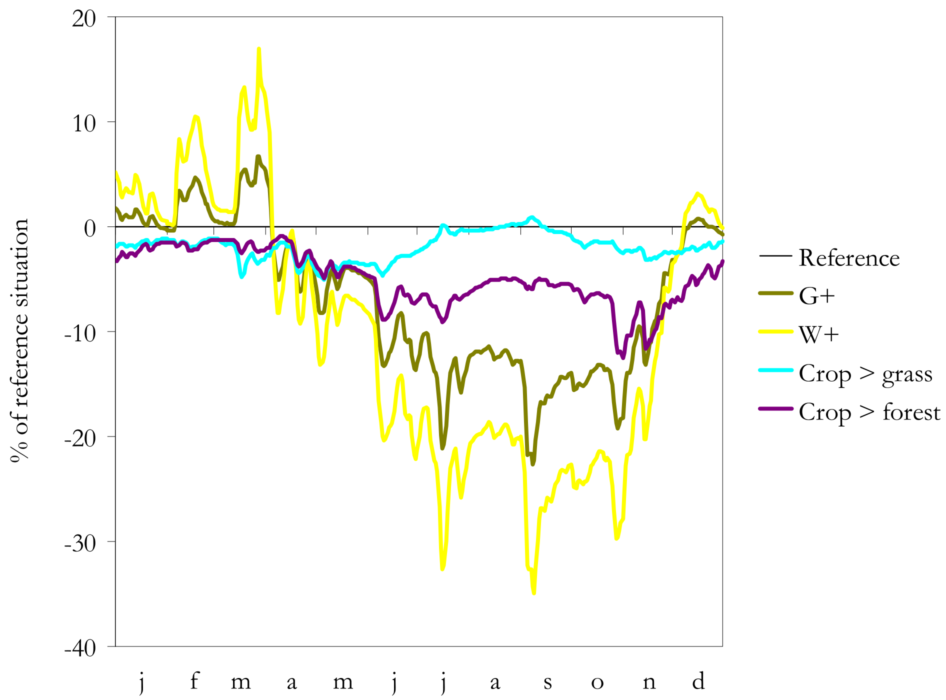

Figure 6.5
The average daily flow relative to the reference situation in % (for the year 1992).

6.3.3 Effects on droughts

To study the effects of changes in land use on droughts, a threshold value of Q90 was added to the reference situation (Figure 6.6), the differences are so minimal that they are not well visible in Figure 6.6. In Table 6.6 the figures are given for the years 1990 till 1995. The drought duration (days below the threshold level) in the period 1990-1995 increased by 21% for the scenario crop to grass and by 46% for the scenario crop to forest. The severity of the droughts increases as well by 13% for the crop to grass scenario and by 58% for the crop to forest scenario. The number of droughts increases from 14 to 15 in the crop to grass scenario and to 19 in the crop to forest scenario.

Table 6.8 has been added to show the differences between the discharges more clearly. The graph of the year 1991 has been left out because the differences between the lines were not visible. Table 6.8 shows that the difference between the scenarios are for the year 1991 more or less the same as for the time period 1990-1995.

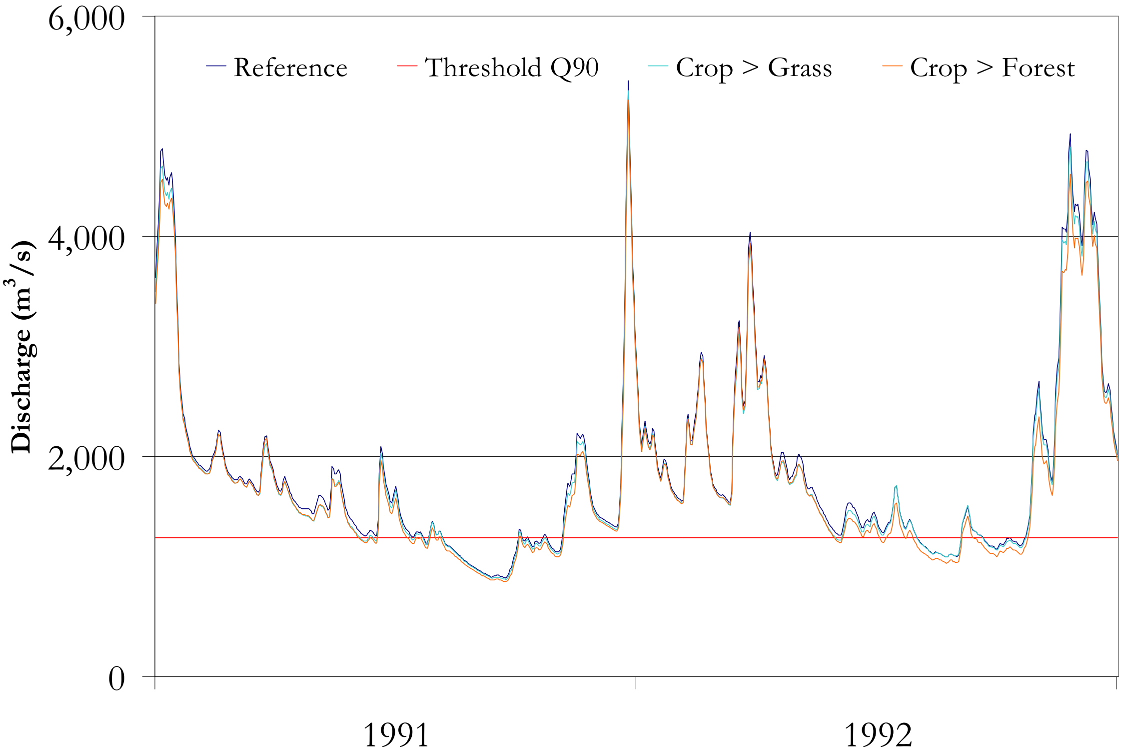

Figure 6.6
Discharges at Lobith for the reference situation together with the land use scenarios for the period 1991-1992.

Table 6.6
Drought analysis for the flow at Lobith for the period 1990-1995.

	Reference	Crop > grass	Crop > forest
Days in drought	220	265	320
Change in % of ref. situation		121 %	146 %
Severity of drought (m^3)	2 175 x 10^6	2 456 x 10^6	3 434 x 10^6
Change in % of ref. situation		113 %	158 %
Number of droughts	14	15	19

7 Drought analysis in the Neckar basin

7.1 Introduction

To understand the spatio-temporal development of a drought in the Rhine basin, the spatial characteristics of the droughts in a particular sub-basin have been studied. In this chapter the drought behaviour in the Neckar basin will be presented. Because of the limited time to conduct this study and the complexity of the whole Rhine basin, only the Neckar basin has been studied (Figure 7.1), instead of the whole basin.

The Neckar basin has an area of 13,958 km2 (CHR, 1978). The origin of the Neckar can be found at Villingen-Schwenningen at 720 m.a.s.l. The Neckar flows after 367 km at Mannheim into the Rhine.

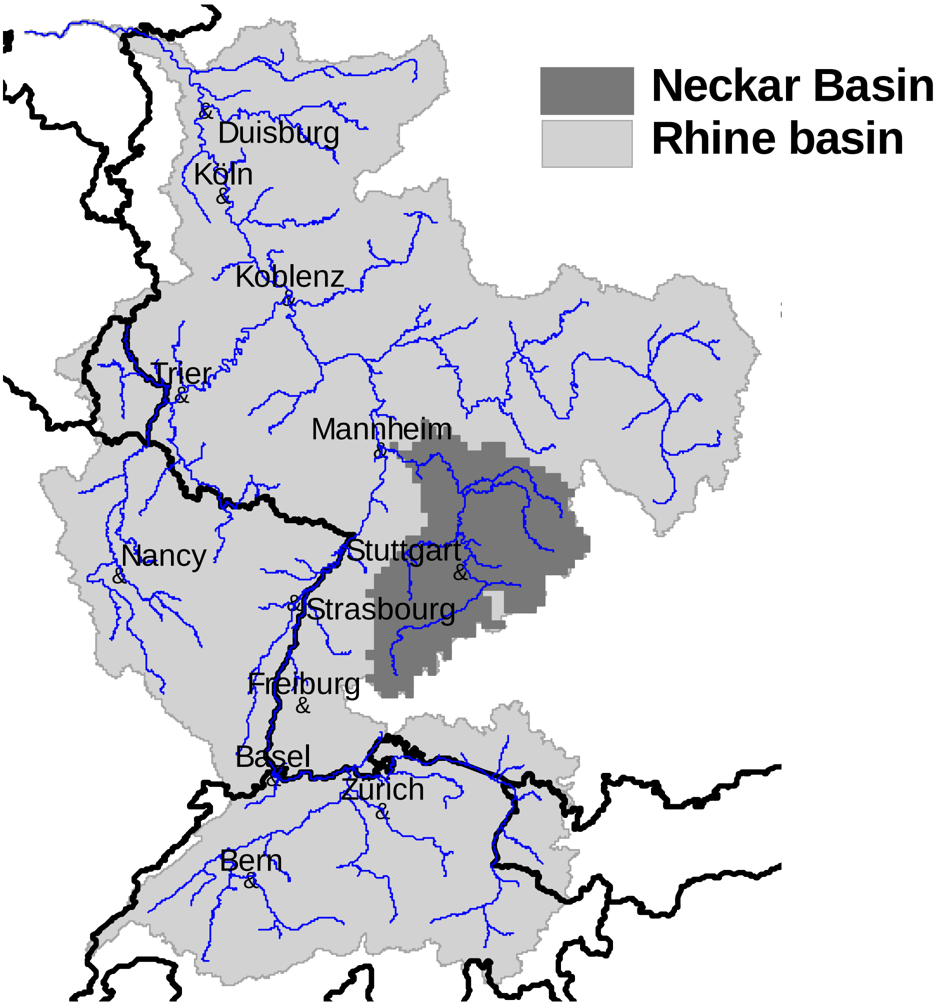

Figure 7.1
Location of the Neckar basin within the Rhine basin.

7.2 Precipitation

Figure 7.2 shows the precipitation and the potential evapotranspiration in the Neckar basin for the period 1961-1995. This data has been taken from the weather station Stuttgart, a representative HBV region (Figure 4.8) in the middle of the Neckar basin.

The annual precipitation shows major differences. The annual precipitation minus the potential evapotranspiration ranges from about 0 to 800 mm (1961-1995). There are four years with low precipitation (1964; 1971; 1976 and 1991). To study the droughts one specific drought period has been selected for this study, being 1991.

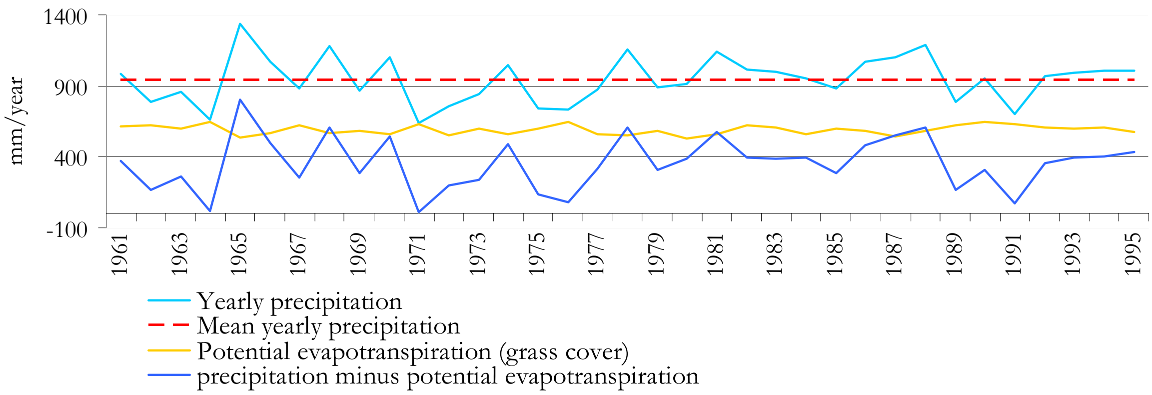

Figure 7.2
Precipitation and potential evapotranspiration (grass cover) for the Neckar basin (1961-1995).

7.3 Stream flow

The stream flow has been analyzed with AlterrAqua (Section 2.4) in two ways: by studying the discharge at the outlet of the Neckar basin (Figure 7.3) and by studying the drought in discharge at the outlet of each sub-catchment within the Neckar basin (Figures 7.4 and 7.5).

For the identification of droughts a threshold value of Q90 has been chosen. Figure 7.3 shows the simulated discharges at the outlet of the whole Neckar basin for the period 1985-1995 with a threshold value of Q90. In Table 7.1 the droughts in discharge can be found that were identified at the outlet of the Neckar basin.

The 1991 drought is with a duration of 119 days by far the longest drought in the period 1985-1995. The spatially distributed start (onset) and the duration of the 1991 drought in the stream flow for each sub-catchment has been investigated. Figure 7.5 shows that a long drought period in the stream flow in the downstream part of the basin does not automatically mean a long drought period in the stream flow in the upstream parts. There are sub catchments in the Neckar basin that only show droughts (in the selected period) in their stream flow for a period of 1 to 20 days instead of the 119 days in the flow at the outlet of the whole basin (and in most of the sub-catchments).

Table 7.1
Droughts in discharge (with Q_{90}) for the Neckar basin for the period 1985-1995.

Start of droughts	Duration (days)
06-10-1985	32
14-08-1989	82
16-11-1989	29
01-08-1990	54
17-10-1990	12
13-07-1991	119
12-08-1992	21
11-09-1992	43

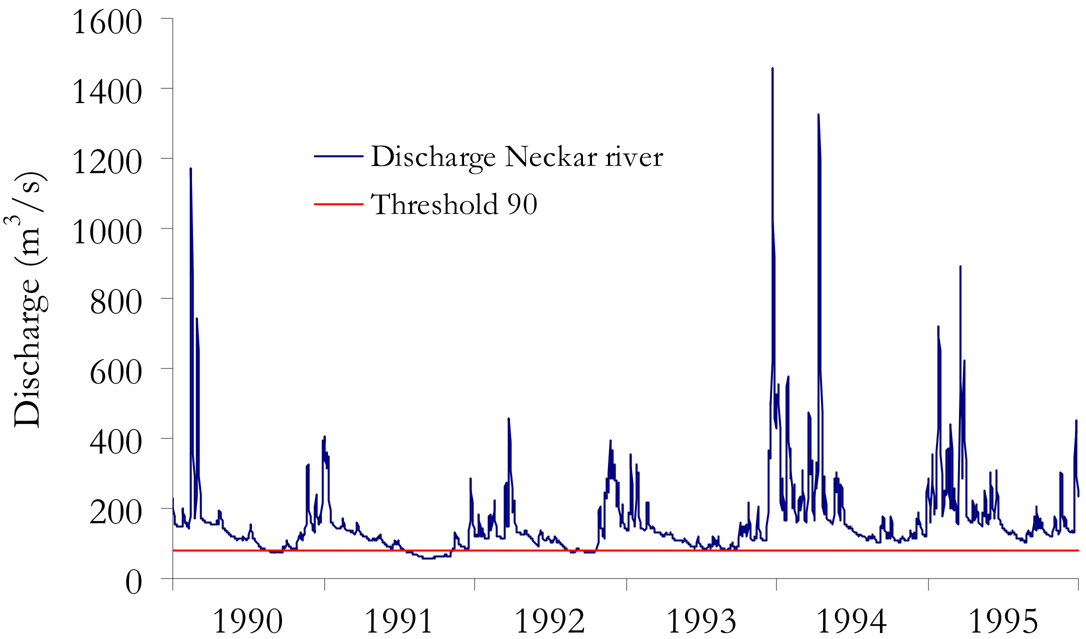

Figure 7.3
Simulated discharge at the outflow of the Neckar basin with a Q_{90} threshold for the time period 1990-1995.

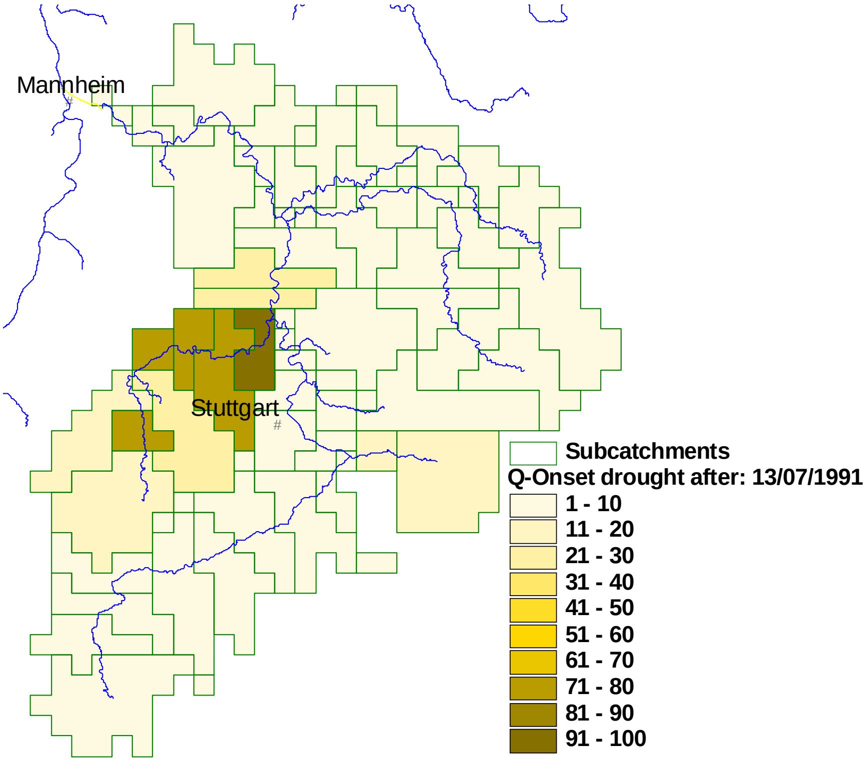

Figure 7.4
Start of drought in stream flow in the sub-catchments of the River Neckar, after 13-07-1991.

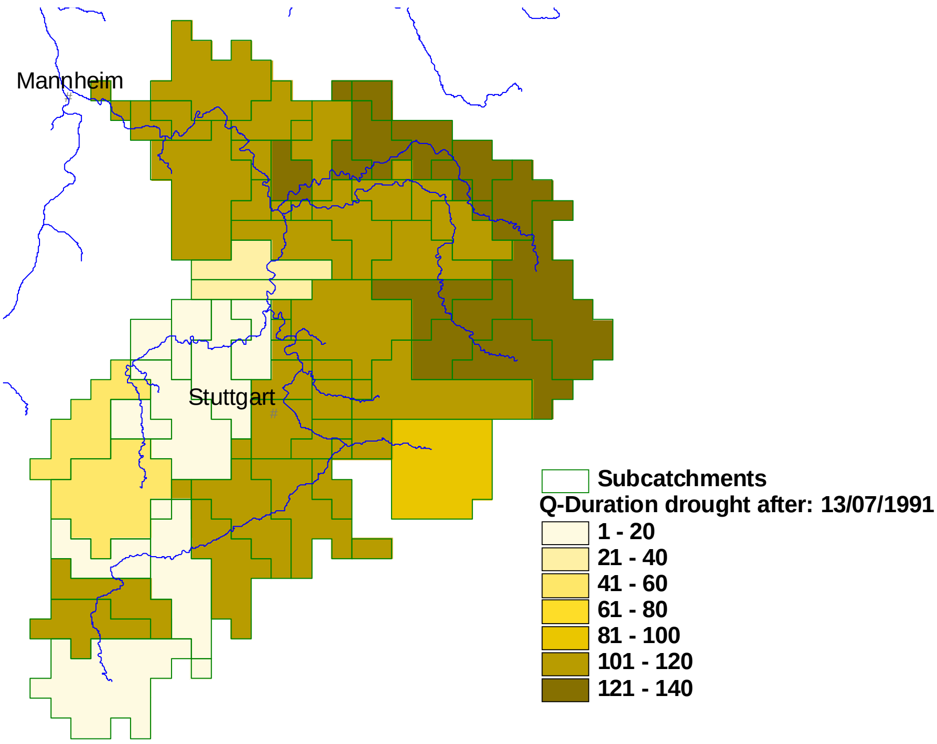

Figure 7.5
Duration of drought in stream flow in the sub-catchments of the River Neckar, after 13-07-1991.

7.4 Groundwater levels

Figure 7.7 shows the simulated groundwater levels for node 4368, which is located in the North-Western part of the Neckar basin (Figure 7.6). In this figure the threshold of H_{90} has been used to identify droughts in groundwater levels. The groundwater level returns each winter back to a more or less the same level, even after the dry summers of 1990 and 1991. This implies that no multi year droughts in groundwater develop. In almost each year (with an exception of 1985, 1987 and 1995) droughts occur in the groundwater levels. The conclusion that were made from this groundwater node are generally applicable on all groundwater nodes in the Neckar basin.

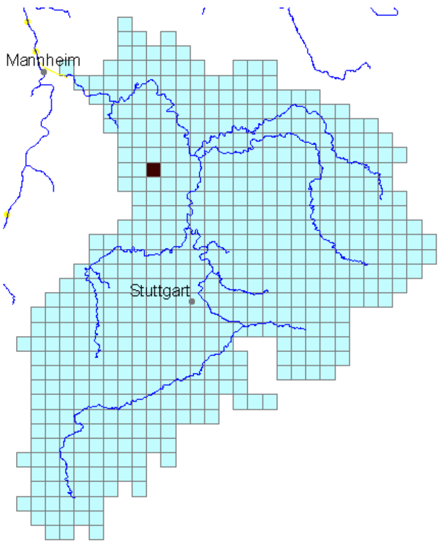

Figure 7.6
Location of node 4368 in the Neckar basin.

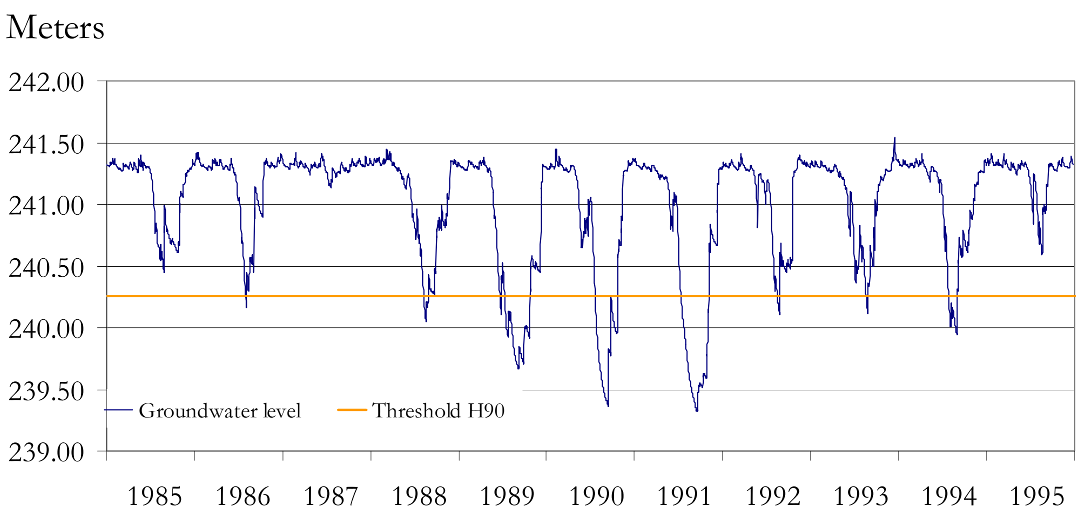

Figure 7.7
Groundwater levels with a H_{90} threshold level for node 4368.

In figure 7.8 the area with groundwater in drought (with a threshold value of H_{90}) throughout the whole Neckar basin is presented. This is combined with the precipitation. In figure 7.8 only the period 1991-1992 is shown, which includes the drought of 1991. The area with groundwater in drought in the Neckar basin reacts fast on high precipitation amounts. This is clear at the end of the major drought event in 1992 were the area in drought suddenly drops steeply because of the high precipitation. Note that the precipitation (Figure 7.8) is a moving average of the precipitation of seven days, so this is not the actual daily precipitation amount.

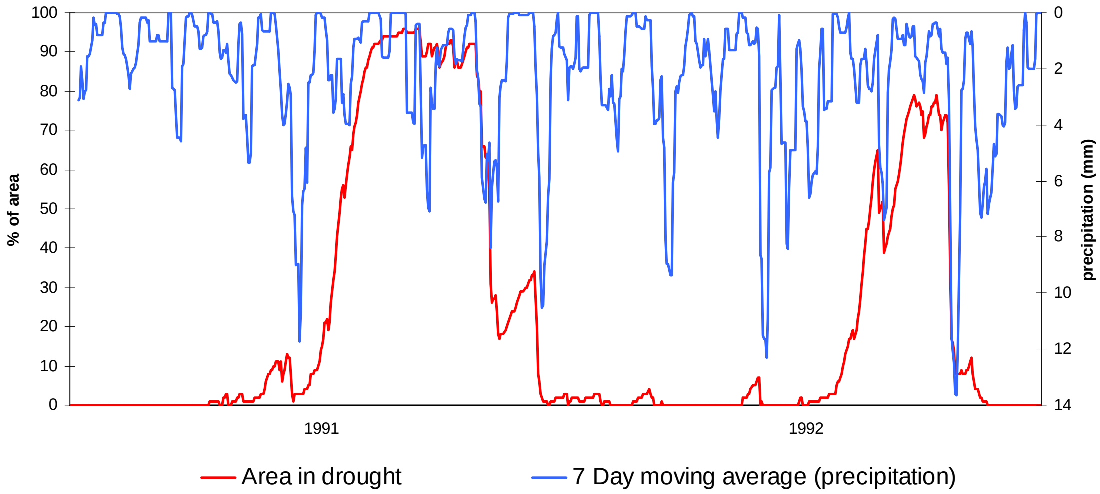

Figure 7.8

Area with groundwater in drought with the 7-day moving average precipitation (area: Neckar basin, period: 1990-1992).

In Figures 7.9 and 7.10 the spatial distribution of the onset and the duration of the 1991 drought is shown for groundwater. In Figure 7.9 the day when the drought starts is presented. Close to the stream the drought starts later. The duration of the drought in groundwater near the southern and in the eastern streams is long, on the other hand near other streams, some nodes show a short drought duration

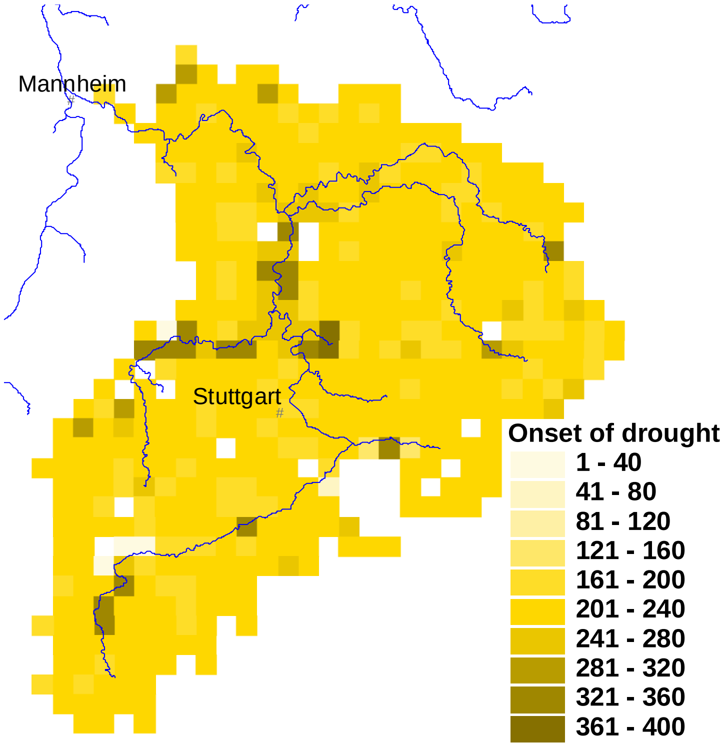

Figure 7.9
Start of drought in groundwater (with H_{90}) after 13-07-1991.

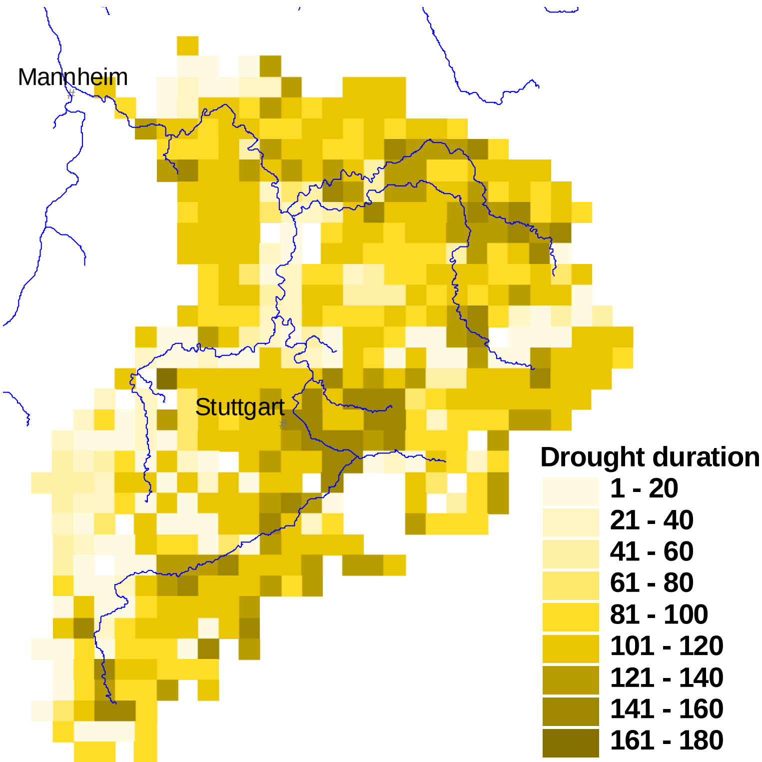

Figure 7.10
Duration of drought in groundwater (with H_{90}) after 13-07-1991.

7.5 Discussion

A drought in a certain hydrological variable (such as: river flow, soil water, groundwater, precipitation and groundwater recharge), does not directly mean that it is a drought for each sector. For example, a drought in soil moisture can have a negative effect on agriculture, but can have a positive effect on groundwater resources for drinking water, if groundwater recharge increases. So it is important to keep in mind that a drought is a very broad term and is not the same for each sector.

8 Conclusions and recommendations

8.1 Conclusions

Improvements to the input data

This study resulted in an improved SIMGRO model for the Rhine basin. The improvements made to the input data of the previous model (Querner, 2009) has led to a considerably better performance of the model. The model with the new input data has an average Nash-Sutcliffe modelling efficiency E of 0.73, as compared to the -0.50 of the model with the original input data. The outflow of the research area (Lobith) has also shown a substantial improvement from 0.26 with the original input data to a very encouraging 0.89 with the new input data.

In the last step of the changes in the input data, two parameters were changed. The transmissivity (kD) values and the soil-water characteristics (moisture content of the root zone and the storage coefficient) were spatially distributed. However these changes of the input date led for the discharges of the Main and Moselle basin to a reduction in the modelling efficiency (Table 5.1). From all the changes to the input data, the change in meteorological data appeared to have improved the model the most.

Climate change

With a changing climate and considering the scenarios with a change in air circulation, it is expected that the discharge of the Rhine at Lobith will decrease on average by 5% (G+) to 8% (W+). Hydrological extremes (droughts and floods) will be for most sub-basins more intense. Minimum discharges will be lower, with at Lobith a decrease in the mean yearly minimum daily discharge by 10% (G+) to 17% (W+). Maximum discharges will be higher, with at Lobith an increase in the mean yearly maximum daily discharge by 2% (G+) to 6% (W+).

Droughts in the discharge for Lobith in the Rhine basin will be more common in 2050 with an increase of 117% (G+) to 197% (W+) in the drought duration. The severity of drought events (volume of water below the defined threshold of Q90, being 1265 m3/s) will increase by 182% (G+) to 406% (W+).

Land use change

The changes of land use from crop to grass and crop to forest have an impact on the discharges in the Rhine basin. The change differs place to place in the basin. The whole basin will experience for both, cropland to grass (c>g) and cropland to forest (c>f) scenario, a decrease in mean discharges (Lobith: c>g: 1.7%; c>f: 4.0%), mean yearly minimum daily discharges (Lobith: c>g: 0.3%; c>f: 4.1%) and mean yearly maximum daily discharges (Lobith: c>g: 1.6%; c>f: 3.3%). For the crop to forest scenario, the changes in the discharges throughout the Rhine Basin are much more than for the crop to grass scenario.

For both land use scenarios the drought duration will increase. For the crop to grass scenario the duration will increase by 21% and for the crop to forest it will increase by 46%. The severity of the droughts increases as well, by 13% for the crop to grass scenario and by 58% for the crop to forest scenario. The results from the different scenarios show that climate change has a much larger impact on discharges and droughts than extreme changes in land use.

Droughts in the Neckar basin
The annual precipitation in the Neckar basin shows major differences. The annual precipitation minus the potential evapotranspiration (grass cover) ranges from about 0 mm to 800 mm (for the period 1961 to 1995).

With a threshold value of Q90 at the outflow of the Neckar basin, eight drought events are found (for the period 1985-1995). The dry year 1991 is identified as a very severe drought in the discharge at the outlet of the Neckar basin. When the discharge at the outlet of the Neckar basin is in a long drought (e.g. 119 days, 1991 drought) it does not imply that streamflow of all sub-catchments throughout the whole basin are in a long drought as well. So there is a clear spatial differentiation in discharge droughts throughout the Neckar basin.

Groundwater levels prove as well that the Neckar basin reacts fast on precipitation. Furthermore the groundwater level returns each year back to the winter level, even after severe droughts in groundwater, which implies that no multi-year droughts develop.

8.2 Recommendations

This research was the second step in using and developing a SIMGRO model for the Rhine basin. This report contributes to a further development. The next recommendations can help to define the following steps:
- The model performs with the newly spatially distributed *kD* values and soil-water characteristics less good in the Main and Moselle basin. The input data needs to be adapted in such a way, that the performance of the model improves.
- Intercompare the SIMGRO model with other types of models (e.g. HBV, VIC), for the Rhine basin.
- Update the time series of meteorological data to include recent droughts (e.g. the severe 2003 drought).

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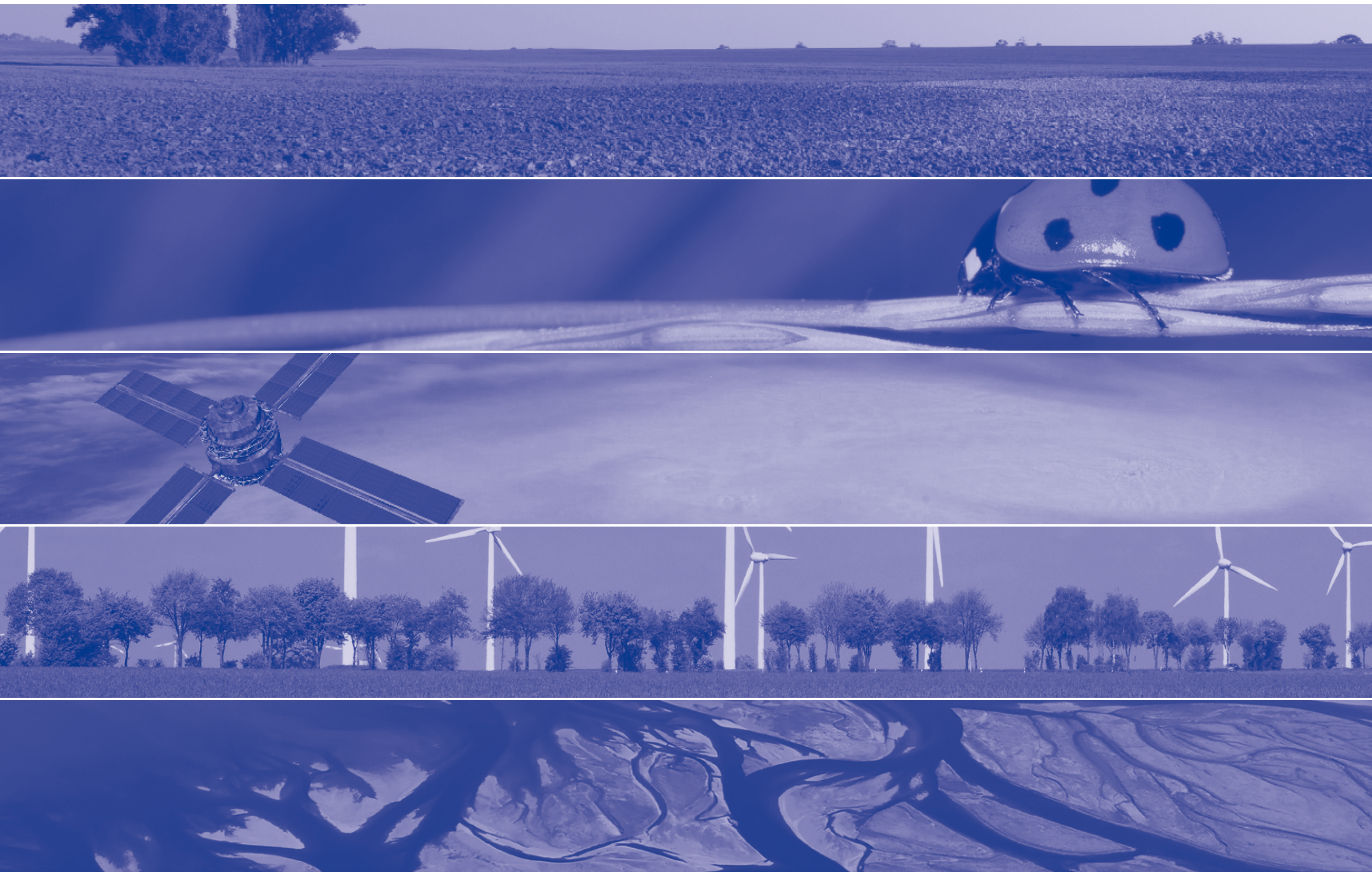

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