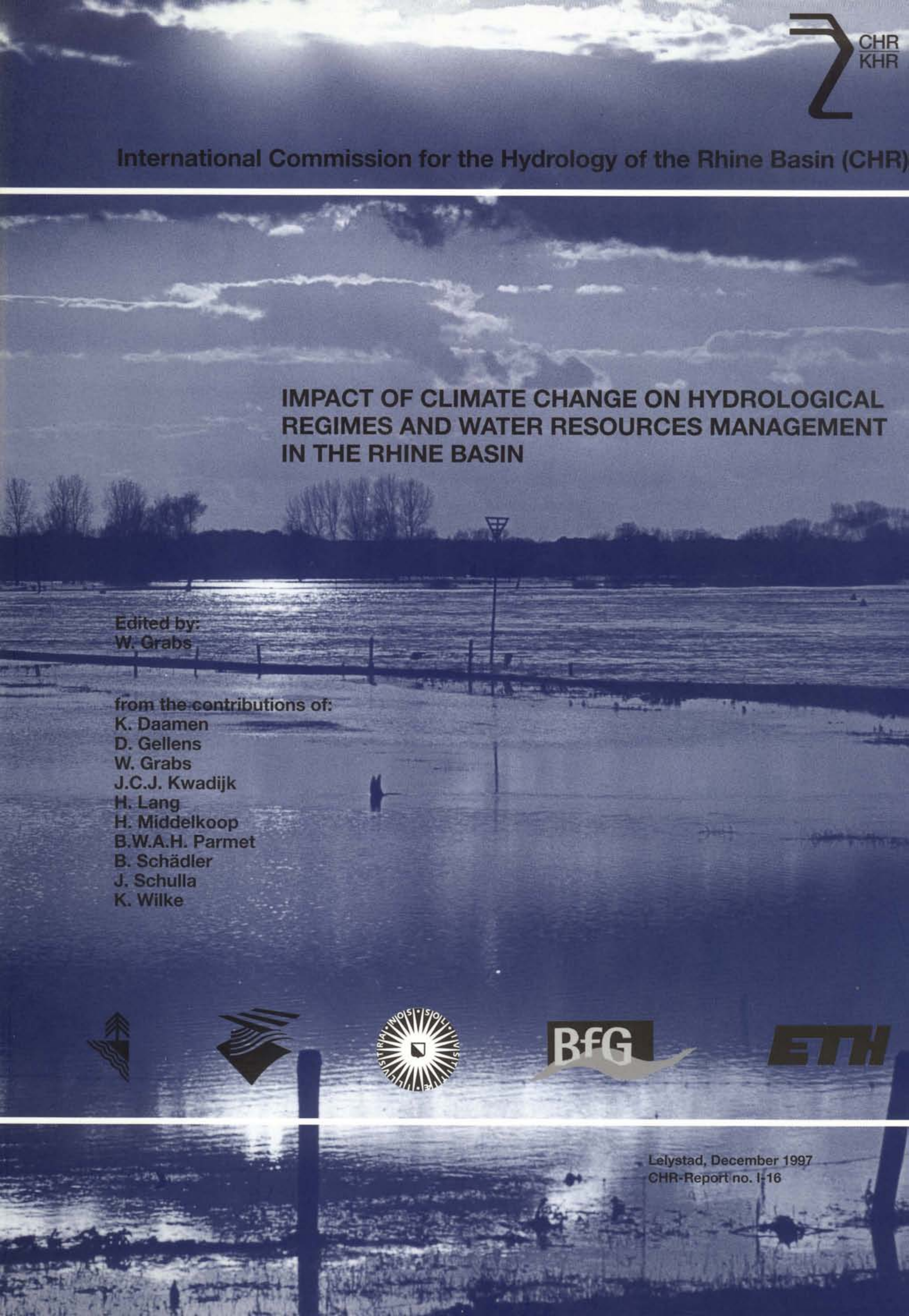

CHR
KHR

International Commission for the Hydrology of the Rhine Basin (CHR)

IMPACT OF CLIMATE CHANGE ON HYDROLOGICAL REGIMES AND WATER RESOURCES MANAGEMENT IN THE RHINE BASIN

Edited by:
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BfG
ETH

Lelystad, December 1997
CHR-Report no. I-16

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Landeshydrologie
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Foreword

A key objective of the International Commission for the Hydrology of the Rhine Basin (CHR) is to support the co-operation between Hydrological Institutes and Services in the Rhine basin and to facilitate studies and research on the hydrology of the Rhine basin, including the dissemination and exchange of information. The focus is on application-oriented research that should provide a sound scientific basis for guidance and recommendations to decision-makers at both the planning and policy levels.

This study of the CHR has been carried out as part of a project of the European Union entitled 'Impact of Climate Changes on hydrological regimes and water resources in the European Community'. The project has an important function in bridging gaps between catchment scale studies, the regional scale studies (based on the findings of changes of the Rhine river regime itself), and the European scale studies. The compilation of a comprehensive GIS database for the entire Rhine basin has been a major achievement in accomplishing the project objectives.

The findings of this study demonstrate the expected impacts of climate changes on the hydrological regime of the Rhine river and its tributaries. Though the study follows the classical impact approach in a straightforward analysis of causes and effects, the climate-impact study also considers other influencing factors such as land use changes. A major achievement is that the climate change impacts on hydrological regimes are translated into an understanding of the consequences of hydrological changes for important river functions. On the basis of this impact assessment, a direction for a pro-active response strategy is outlined and supported by policy recommendations for selected impact areas including: floods and low flows, inland navigation, water supply, hydro-power production, and winter tourism in the Alps.

Within the framework of the CHR project, six research groups contributed to the present study. These are: Institute of Geography at ETH Zürich, (ETH); Swiss National Hydrological and Geological Survey (LHG), Bern; Royal Meteorological Institute of Belgium (IRMB), Brussels; Federal Institute of Hydrology (BfG), Koblenz; Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA), Arnhem; Department of Physical Geography at Utrecht University (UU). We would like to thank all members of these groups for their very important and valuable contributions to this research project. Special thanks go to the CHR project co-ordinator, Wolfgang Grabs, who successfully conducted the project to its end, and who compiled the final report. Finally, we would like to thank the sponsors of this great project: the EC, the Swiss Federal Office for Education and Sciences, and all the above-mentioned collaborating institutes.

The President of the CHR

Prof. Dr. M. Spreafico

CONTENTS

1 General introduction and objectives

The CHR study presented in this report is part of an EU-project entitled 'Impact of climate change on hydrological regimes and water resources management in Europe'. The CHR contribution to the project concentrates on the regional scale (the modelling of the entire Rhine basin) and the catchment scale (modelling of selected sub-basins of the Rhine basin). The time horizon for the results of the study is the year 2050. Figure 1.1 provides an overview of the Rhine basin and the selected subbasins. The principal objective of the CHR contribution has been to make an assessment of the impacts of climate change on the hydrology of the Rhine river, based on the results of hydrological simulations using presently available climate change scenarios. The simulations have formed the basis for a semi-quantitative estimate of the consequences of hydrological changes on selected impact areas, and the project resulted in the development of an anticipatory adaptation strategy as a response to climate changes. The table below gives the CHR contribution to the principal results of the entire project:

Table 1.1 Expected project results and CHR activities

Project Results Identify potential impacts on water resource availability, flow regimes and drought on EC scale **(Result 1)**	Main CHR Activities The regional Rhineflow (RF) model and the catchment models are run with the baseline climatology and scenarios provided; Indicators for the impact of climate changes on water resources & hydrological regimes are determined.
Review variability in runoff regimes to characterise vulnerability of EC water resources **(Result 2)**	Assessment of variations in runoff as a result of climate changes is prepared on regional and catchment scales.
Identify climate change impacts on river flow regimes throughout the Rhine basin **(Result 3)**	Assessments are made on regional and catchment scales, results of the RF model are compared with results of the catchment models on the basis of best-fit models of subbasins of the Rhine.
Examine changes in the effect of climate changes for regional and catchment scales **(Result 4)**	Calibrated and validated catchment models are run with scenarios. Impact of climate change scenarios on selected impact areas viz: floods, low flows, inland navigation, water supply, hydropower generation is assessed; Policy direction and policy guidelines are developed as a flexible response strategy.
Compare climate change effects with effects of non-climate changes (land use) **(Result 5)**	Impacts of land use changes on the flow regimes are assessed on region al scale.

A major activity has been the composition of a geo-referenced information base about the entire Rhine basin and its subcatchments including the compilation of a hydro-meteorological database for the models. The preparation of the database in itself is seen as a major contribution to the regional scope of the project. The database is the basis for monitoring activities with regard to changes in the basin as a whole as well as in selected subbasins of the Rhine river.

From the start of the project, there was consensus among the project partners that model development had to be focused on the application of the models. Therefore, no new models were developed but existing models were improved, adapted and tested under the various catchment conditions. The regional and catchment models were calibrated with observed data, compared with baseline climate scenarios, and then used for the simulation of impacts of climate changes on the hydrological regimes of the subcatchments and the entire Rhine basin. The map below shows the Rhine basin and the subcatchments of the Rhine which are under investigation.

In developing the model, the project group agreed that it should be possible for the climate scenarios provided by the Climate Research Unit (CRU) to be run with minimum calibration time and adjustment of model parameters. The aim was to provide tangible results with regard to indications of impacts of climate changes on the hydrological regimes of the rivers investigated, and subsequent impacts on human activities of high socio-economic importance such as inland navigation, power generation, design floods, land use, agriculture and tourism. The downscaling of given climate change scenarios was achieved by interpolation of GCM outputs from 2.5° to 0.5°. The downscaled scenarios were input in the CHR part of the project. The validity and reliability of these scenarios, especially on the catchment scale, is the subject of discussion throughout the report.

To achieve consistent results on the regional (Rhine) and catchment scales (subcatchments of the Rhine) a conceptual model (the RHINEFLOW model) on the Rhine was developed and applied, and the results of the catchment models were compared with the regional scale model. In the study, different model concepts have been used under the assumption that each model is a 'best choice' for modelling the vastly differing environmental conditions and hydrological processes within the Rhine basin, which vary from high alpine conditions to the lowland conditions near the mouth of the river. The model results are comparable with and can be linked to the results of the RHINEFLOW model. Vice versa, the results of the RHINEFLOW model are tested for their plausibility on the basis of the results of the catchment models. Consistency is achieved by using the same climate scenarios for all catchments and models. The regional model has been compared with data sets of the catchment-scale basins with a resolution of 1 km × 1 km.

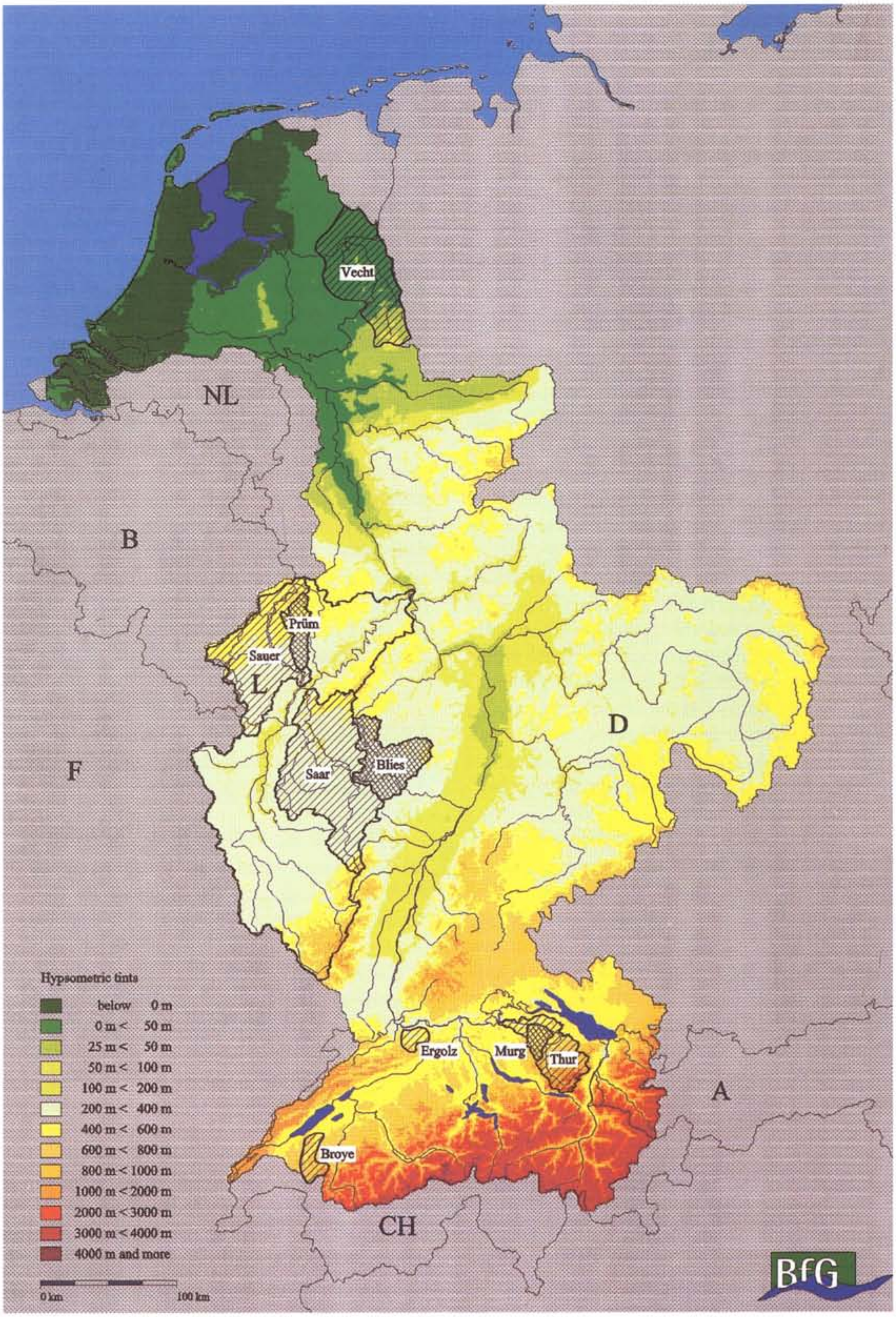


Figure 1.1 Overview of the River Rhine basin and study areas

2 Executive summary of principal achievements and results

The GIS supported data compilation necessary for development and calibration of the model may be regarded as a major achievement and a cornerstone for the entire study. The regional scale model (the RHINEFLOW model) and the models for selected subcatchments have been developed and applied both on the baseline and climate change scenarios provided by the Climate Research Unit (CRU) of the University of East Anglia.

With regard to the application of the different models, the most important result is, that generally speaking the subcatchment model results are consistent with the overall results of the RHINEFLOW model. Using the results of the subcatchment model runs of the climate change scenarios it is furthermore possible to fine-tune the regional RHINEFLOW model. In general, the model results indicate a change in the Rhine's hydrological regime and – to a varying degree, but most pronounced in the alpine catchments – a shift in the hydrological regimes of the subcatchments of the Rhine basin coupled to a likely increase in the frequency and intensity of extreme hydrological events as a result of the present-day perspective of climate changes.

The impacts of these changes are assessed for winter tourism in the Alps; the possible impacts of land use changes are assessed for the entire Rhine basin by combining land use and climate change scenarios. While the winter tourism has a direct effect on the Swiss economy, the land use changes are of high interest for decision-making in the agricultural sector of the European Union. The results also show the directly tangible benefits of the project regarding decision support activities.

2.1 Development of a comprehensive GIS supported database

The development of the RHINEFLOW model and the subcatchment models made it necessary to set up a comprehensive database of the topographical, meteorological, hydrological and landuse conditions of the entire Rhine basin on a very detailed scale using a Geographic Information System (GIS). The compilation of this most comprehensive database of its kind for the Rhine basin required extraordinary efforts in terms of obtaining, processing and storing the data in a format for the use in hydrological models of the entire Rhine basin as well as subcatchments. Details of the database are described in chapter 7 of this report.

2.2 Development and calibration of the regional model and application of the climate change scenarios

The RHINEFLOW model has been developed as a conceptual water balance model on a 3 × 3 km grid and a monthly time resolution. The model was tested with existing data and calibrated for the project with the baseline climate scenario supplied by CRU. Following this calibration, the climate change scenarios were applied. This approach is similar to the approaches of the catchment models. The model results are consistent with the results of the catchment model studies.

2.3 Development and calibration of the catchment models and application of the climate change scenarios

Use was made of deterministic hydrological models developed by the Federal Institute of Hydrology, Koblenz, the Institute for Inland Water Management and Waste Water Treatment, Lelystad, and the Swiss Federal Institute of Technology, Zürich. A conceptual model developed by the Royal Belgian Institute of Meteorology, Brussels was applied by the Swiss Hydrological Survey. The models were calibrated and applied to representative parts of the Rhine basin, including: selected alpine catchments (Thur basin (1,700 km^2)), pre-alpine catchments (Broye (392 km^2), Ergolz (261 km^2), Murg (212 km^2)), the middle hill region (Blies (1,888 km^2), Prüm (574 km^2)) and the lowlands of the Rhine (Overijsselsche Vecht (5,600 km^2)). To maintain consistency in the results on all scale levels, all models were calibrated against a baseline climate scenario. All supplied climate change scenarios were subsequently applied and compared with the result of the baseline climate scenario run.

2.4 Principal results of the RHINEFLOW model

The results of the application of the conceptual RHINEFLOW model with the climate change scenarios indicate, that the hydrological regime of the Rhine will shift from a combined rain-snow fed regime to a rain-fed regime. The results indicate that peak flows will increase in the winter period and that low flows will become more pronounced and frequent during the summer and autumn seasons. The most dramatic changes in the discharge regime can be expected in the alpine region, which is considered to be the 'Water Tower' of Central Europe. The implementation of climate change scenarios belonging to different time horizons allows estimation of the vulnerability of river-based activities such as inland navigation, drinking water supply, irrigation and tourism. It must be noted that the bandwidth of the results is large and does not allow for further quantification at present.

2.5 Principal results of the catchment models

Alpine catchments

Typical of the subcatchments of the Rhine river in Switzerland are the vast altitude ranges in excess of 1,000 metres along the course of the rivers considered. For the Swiss prealpine/alpine region a semi-distributed, physically based catchment model (Water Balance Simulation Model (WaSiM – ETH) has been developed which is capable of simulating the water balance and discharge for daily and shorter time steps thus representing the fast hydrological response typical of prealpine/alpine catchments. Application of the model with the supplied scenarios shows, that in future winters the discharges will increase largely because rising temperatures lead to an increase in the liquid phase fraction of total precipitation when compared with the present-day situation. This means, that the storage capacity and regulatory function of the winter snow cover will decrease. As a consequence, summer flows will decrease. In addition, less summer precipitation and increased evapotranspiration will cause decreasing soil moisture and less groundwater recharge. At the same time summer floods are decreasing by 4 to 11%, while winter peak flows with a 50-year return period will rise by 9 to 16%. The flood perspectives will be more pronounced in the higher altitudes and the low flows will increase more in the lower parts. An altitude dependent statistical analysis of the snow conditions shows that in regions below 1,000 m.a.s.l. snow cover duration may drop drastically, with the corresponding consequences for winter tourism.

Prealpine catchments

For the prealpine/alpine catchments of the Murg, Ergolz and Broye catchments in Switzerland, an existing daily conceptual hydrological model (the Integrated Runoff Model – F. Bultot, IRMB) has been refined to simulate hydrological processes and fluxes in a very detailed way and represent the water balance for small and medium scale catchments as well as the hydrographs at the outlet of the basins. Following its improvements regarding the daily estimates of interception, throughfall, evapotranspiration, surface runoff and percolation processes for eight soil cover types, the model is particularly suitable for assessing impacts of modifications in the vegetative cover. The model was applied with the supplied climate change scenarios to estimate impacts of climate change on the snow cover in the Broye catchment. The impact is dramatic and shows a significant reduction of the snow cover. It is reasonable to assume, that in the intermediate scenarios only every second winter will be a good season for winter sport resorts between 1,200 and 1,500 metres a.s.l. The 2 × CO_2 scenario indicates that winter sports conditions below 1,500 metres a.s.l. will generally become unfavourable. This has an adverse effect on the winter tourist industry in Switzerland which is a very important sector of the Swiss economy. The downstream effects of a decreasing snow pack storage on the Rhine river have already been mentioned.

Middle hill catchments

The middle hill region of the Rhine basin is represented by the Mosel basin. The Sauer is an important tributary to the Mosel, and the Prüm basin has been modelled as a subcatchment of the Sauer basin at present. The model used is a semi-distributed conceptual model (Hydrological Simulation Program Fortran (HSPF9)). The model uses the concept of similar hydrological response units within the subcatchments of the modelled basin. A daily time step was used for the model computations. Generally speaking, the scenario simulations simulate that runoff decreases between July and November as a result of decreasing precipitation and increasing evapo-transpiration. For December and January most scenario simulations show an increase in mean monthly runoff. Though the flow regime of the Prüm middle hill catchment does not change significantly, it seems that the variation in runoff becomes greater. This finding is largely consistent with the other catchment findings which indicate a general tendency towards increasing frequencies and absolute values of extreme events.

Lowland area

For the lowland part of the Rhine basin, the catchment of the Overijsselsche Vecht has been chosen for the development, calibration and application of a lowland model with a physical basis combining a hydrological process component and a flow-routing component. The hydrological component of the model computes the actual daily evapotranspiration and discharges for the subcatchments of the basin. The data for the different combinations of land use, soil physical properties and seepage is provided in a Geographical Information System which allows for the simulation of changing environmental conditions in relation to climate change scenarios. In general, the simulation results for the climate change scenarios show a maximum discharge reduction in September and a considerable increase in high and maximum daily discharges in the January- March period. Maximum daily flows will increase dramatically. Days with low discharges as well as high discharges are computed to occur more frequently, which underlines the notion of increasing frequencies and absolute values of extreme hydrological events as a direct response to climate changes.

2.6 Effects of land use and climate changes

Land use scenarios were developed for the entire Rhine basin for the 2040-2049 period. The landuse scenarios are based on biophysical and socio-economic developments. The simulation results for present and future climate changes suggest a positive effect on the overall suitability of land for cultivation of crops and tree species. Analysing the bio-physical part of the land use and climate change scenarios it is assumed that around halfway the next century yield levels of agricultural production will have reached 90% of the water-sensitive yield in all regions of the Rhine basin. It is anticipated from the model simulations that, with a contracting agricultural area, there is a tendency to grow crops in those parts of the Rhine basin that have the highest yields. There is a notion however, that with decreased lowflow discharge in the Rhine and – more pronouncedly in smaller rivers and rivulets of the Rhine used for diversion of irrigation water – irrigation-fed intensive horticulture cash crops may be affected if irrigation has to be curtailed in the summer periods.

3 Socio-economic implications of hydrological changes – an overview

As a result of anticipated hydrological changes, the socio-economic environment will be subject to considerable impacts. All river functions (including safety, inland navigation, nature, water availability) are influenced to some extent. The results of present climate scenario simulations contain a high degree of uncertainty. As a result, these uncertainties are also present in the quantification of anticipated impacts.

However, for the *direction* of the impacts the uncertainties are relatively small. An increase in temperature will cause a decrease in snow storage during the winter in the Alps. Precipitation is expected to increase during the winter period. This leads to higher discharges during the winter period. Evapotranspiration is expected to increase because of the temperature rise, despite a more efficient use of water by some crops. With a decrease in precipitation during summer this leads to lower discharges during the summer half year. The increase of ablation of the glaciers due the higher temperature will enhance this effect. Even with an alternative scenario with a small increase in precipitation during the summer period, this general shift in the hydrological regime of the Rhine would occur. The changes in the snow regime, caused by an increase in temperature of which we are quite certain, are very important. The average discharge is not expected to change much. The increase in winter discharge is compensated by a decrease in summer discharge.

In all regions of the Rhine basin the frequency and magnitude of peak discharges are expected to increase during the winter period, which will increase the risk of winter floods in the basin. This can have great implications. It may be remembered that the damage during the floods of 1993 and 1995 was about 1.85 billion Ecu in Europe. Of all natural disasters in the Rhine basin, the largest damage is caused by floods.

The decrease in summer discharge is expressed in an increased frequency and duration of low flows. First of all this will affect inland navigation. The number of days at which ships on the Rotterdam-Basel stretch cannot be fully loaded is expected to increase. This is an important impact, in view of the policy to increase the transport capacity of inland waters as a more environment friendly alternative to road transport. It is planned to increase the navigable depth on several reaches of the Rhine river. This may counterbalance the effects of an increase in low flows, but the planned increase in transport capacity may not be reached.

Together with higher temperatures, lower discharges in summer will influence the water quality and will have important effects for aquatic ecology. Present problems with high temperatures are expected to occur more frequently, especially if present trends of anthropogenic thermal pollution remain unchanged. An increase in temperature may have a two-fold effect for terrestrial ecology along the rivers. The acceleration of flooding cycles increase the ecological dynamics of the system which is a positive effect. An increase in low flows, however, may cause water shortage problems and consequently negative effects. It should be noted that, especially in the central and lower parts of the Rhine basin, the landscape planning along the rivers, which is a direct human factor, is the dominant factor with respect to ecology.

The generation of hydropower in the Rhine and in its tributaries is an important economic factor. In the alpine part hydropower generation will be facilitated, because in that region the difference between summer and winter discharge decreases. Further downstream, the opposite is true, and hydropower generation may be negatively influenced by prolonged low flow periods. Where river water is used for cooling purposes, the cooling capacity during the low flow periods will decrease due to higher water temperature. This will increase costs, because other, more expensive, cooling methods have to be applied to reduce negative ecological effects.

The effects for agriculture are difficult to assess. Not only the uncertainties in the climate scenarios play a role, but also the uncertainties in the effects of an increase in CO_2 concentration on crop growth and water use are considerable. In a separate study effects for crop growth and land use in the Rhine basin were investigated. With a moderate climate change scenario, crop production is expected to increase in general. For most crops, a higher atmospheric CO_2 concentration acts as a fertiliser, and an increase in temperature enlarges the area suitable for different crops. Total water use increases, although not as much as can be expected from the increased temperature and increased production. This is because several crops use water more efficiently under circumstances of a higher CO_2 concentration. Taking into account an increase in water use, it is expected that in parts of the Rhine basin which experience water shortages at present, the water shortage problems will increase. This will lead to additional costs, taking into account that the water availability from rivers is expected to decrease. However, major changes in land use are determined by other socio-economic factors.

The above mentioned impacts have a strong regional differentiation, but they play a role in the basin as a whole. There are also some impacts, which are limited to specific parts of the basin. For the alpine part of the Rhine basin, the winter tourism industry is affected strongly. In the Swiss winter sport areas, about 50% of the ski lifts are starting at an elevation below 1500 m a.m.s.l. and 30% of them end below this altitude. In this zone below an altitude of 1500 m a.m.s.l., the temperature rise may lead to such a deterioration of the snow conditions that winter tourism in these areas is threatened. In the delta area of the Rhine, the combined effect of lower summer discharges and an increase in sea level is expected to cause an increase in salinisation problems of shallow aquifers. Furthermore, salt water intrusion in surface water is expected to increase, leading to problems with intake of water for public water supply.

Suggestions for policy responses to the impacts outlined above are described in the next chapter.

4 Summary of policy implications

Climate change is a slow but persistent process; the rate and magnitude of the changes are still not known. The large annual variability of climate and its hydrologic response make it difficult to detect these changes over shorter time periods. On the long run, however, the hydrological impact is expected to be so large that it cannot be neglected in water resources management.

How can water resources management deal with the expected changes, taking into account the uncertainties? There are three possible policy alternatives, 'Immediate Response', 'Wait and Verify', and 'No Regret'. With the ***immediate response*** strategy, extensive measures are taken now to deal with the effects of climate change. This is not recommended because it is presently impossible to quantify with sufficient reliability the climate changes as well as the impacts. Under the assumption of worst case scenarios, large financial commitments are required, at a time when investments cannot be substantiated scientifically and economically. The ***wait and verify*** strategy overlooks the fact that all indications point to the reality of a climate change. To wait until the changes become evident is therefore not recommended. It will almost certainly imply very high costs over a short period of time. Furthermore it should be recognised that the required responses take a planning and implementation period of at least 10 years. Balancing required actions against economic costs and the existing uncertainties in the climate change scenarios we recommend a policy strategy of ***no regret*** in a pro-active way.

Policy of no regret in this context means: Anticipatory adaptive measures are undertaken as a response to the impacts of climate change in combination with on-going activities. At present many measures are proposed and implemented to improve the flood protection. Where possible, so-called win-win situations are created, by combining flood protection with for example ecological rehabilitation of the Rhine river and its basin. Also, measures are taken to maintain and improve the inland navigation possibilities. It is likely that in the future additional measures are required to cope with the impacts of climate change in relation to flood protection, shipping, nature, etc. Therefore it is important that the measures taken today are flexible towards the future. In other words, it should be possible to adapt and extend them relatively easily for changed conditions. For investments with a long expected life-time, like large weirs or storm surge barriers, the design should take the present knowledge on the possible magnitude of long-term changes into account. Adaptation in a later stage is expected to be much more expensive. Furthermore, actions should be taken in a pro-active way. For example, in the forthcoming period one should increase the system's flexibility in water management of the Rhine river.

Under the ***Policy of No Regret***, a prioritisation of planned or on-going activities should be considered. In a general way, some priority areas of action can be outlined:

1) Safety against flooding has top priority, in present and also future water management. A general strategy to increase this safety is based on two pillars. This strategy has been developed in the riparian states of the Rhine river, and it is used as a basis for the Rhine Flood Action Plan. Expected climate changes are increasing the uncertainty for the future. They should be accounted for in the following two pillars:
   a) The pillar aims at reducing peak discharges and peak water levels. This can be achieved by increasing the storage capacity in the drainage basin itself, for example by a more natural land use that enhances infiltration of precipitation water. This is very effective for the smaller local floods. Also, the storage capacity of the river system can be enlarged by adding storage capacity outside the river channel, for example in the form of retention reservoirs. Starting downstream, enlarging the discharge capacity is an effective measure, for example by deepening and widening the river. In view of the changing climate conditions and the inherent uncertainties, additional areas should be reserved in the present plans to be able to cope with a possible increase of peak flows in future. When it becomes evident that these areas are not needed for flood reduction, they can be used for other im-

portant river related functions. These functions should be of such a nature that they can be adapted easily. This is not the case for infrastructure and built-up areas. Instead, areas for nature development or areas used for extensive agriculture can be adapted relatively easily.

   b) The second pillar aims at reducing damage during floods by means of technical measures, by decreasing the damage potential, and by adequate emergency systems. In the planning of technical measures with a long life-time, state-of-the-art knowledge of effects of climate change should be taken into account in the design. Decreasing the damage potential by proper spatial planning of flood plains is by far the most effective way to cope with floods. To account for climate change, also here the right 'recipe' is reserving additional areas, by using stricter rules for a larger area than yet necessary for present-day conditions.

2) The policy of 'no-regret' may not be fully valid for high alpine catchments.

3) Improvement of water resources management strategies should also include hydropower generation, irrigation, and groundwater recharge. Modifications in alpine reservoir management should be considered as an answer to meet the problems of changes in the flow regimes and resulting reservoir inflows.

4) An increase of the storage capacity in the drainage basin may reduce the risk of low flows. When larger amounts of water can infiltrate, the baseflow component from groundwater recharge will increase. Here too, the no-regret principle is valid. Also without an increase in low flows due to climate change, these measures will have a positive effect during low flow periods even under present-day conditions.

5) Inland navigation will remain an important function of the river. In view of the expected volume of transport by inland navigation, additional flexibility in the transporting system should be created. More pronounced low flow periods with lower water levels and longer duration will require a response with regard to shipping schedules, selection of cargo and composition of the fleet. Next to ships with large capacity, also smaller ships that are subject to fewer navigation restrictions may become cost effective in operation.

6) The legal basis of by-laws should be reviewed for their applicability and validity under climate change conditions. For example existing regulations with respect to maintenance of maximum allowable water temperature in rivers or discharge levels below which waste water discharge is not allowed.

7) Present design principles and criteria should likewise be reviewed. Hydraulic structures often have a planned life-time of 50 to 100 years. It should be investigated if and in what way the still uncertain effects of climate change can be taken into account in their designs.

Generally, a pro-active policy of no-regret provides benefits in a cost-efficient way even if the indicated changes may not become true. Extended flexibility in water resources management which is necessary to deal with possible future problems will help solving present-day problems as well. This can be achieved if the political and socio-economic boundary conditions are defined carefully in advance.

5 Scientific issues

5.1 Introduction

The Rhine basin incorporates high Alpine snow and glacier regions, low mountain ranges and the lowland areas. These features make the Rhine unique amongst other river basins in Europe. The runoff regime of the Rhine in Germany is characterised mainly by two effects: during the low water season in summer a major amount of the runoff is generated in the Alps due to melting of snow and ice. The tributaries of the French and German parts of the Rhine do not contribute much to this base flow. Most of the precipitation within the non-Alpine area is taken up by evaporation. The situation changes in winter times: much of the precipitation in the Alpine region is stored as snow and ice whereas in the remaining catchments it becomes runoff. Floods are likely to occur from December to March and are often caused by floods of the main tributaries Neckar, Main, Nahe, Lahn and Moselle accumulating along the Rhine. For example, during the 1993 flood which caused heavy damages both along the Rhine and along its tributaries, the Rhine's peak flow at the Rheinfelden gauge (close to the Swiss-German border) was only little more than 2000 m^3/s, whereas at the Cologne gauge the peak flow was as much as 10800 m^3/s. This example outlines that not only investigations of changes in hydrological regime in the low mountain range are very important for the whole Rhine basin, but also the effects of changes in the tributaries themselves.

The complexity of the Rhine basin and its various hydrological regimes posed a scientific challenge in terms of scale, hydrological diversity and modelling.

5.2 Scope of the project

This project aims at assessing the impact of climate changes and changes in land use on hydrological characteristics and inherent water management on a large river basin. The project involves more than only a straightforward analysis of discharge characteristics under different climate scenario conditions:

1. The project allows an analysis of the response of the hydrological system in different parts of the basin, from the upstream Alpine part, via the German middle mountains to the lowland area. In addition, the effects are compared on different spatial and temporal scales.
2. In addition to climate, scenarios of autonomous land use developments in the Rhine basin are considered as well. By factoring in changes in crop production, the interaction between climate changes and land use is also included.
3. The demands of the functions of the hydrologic system are considered as a criterion for analysis of the consequences for water management. In this way, the study addresses socio-economic impacts of climate changes on the Rhine river. The project enables analysis of changes in critical boundary conditions for the river's functions from the Alps down to the river delta, and also determination to the degree of stress put on these functions.
4. The project demonstrates its transnational nature: hydrological changes in the upstream parts of the Rhine basin may have consequences for the river functions in the downstream stretches. Some of these functions, such as inland navigation, are particularly relevant on the transnational scale.

5.3 General model characteristics

Models can be subdivided according to the way the processes are positioned between two extremes. In physically based models, all components of the hydrological process are described in detail by fundamental laws. On the other extreme we find the black-box models, that do not represent hydrological processes operating in the real world, but describe the process as a whole by means of empirical relationships between inputs and outputs. In between these extremes are conceptual models, which reflect physical laws in a simplified approximate manner and generally involving a certain degree of empirism. The discretisation of space comprises two basic categories. The first category comprises distributed models that take into account the spatial distribution of model inputs, outputs, variables and parameters in a detailed form. This is usually achieved by subdividing an area into elementary units or grid cells. The second category consists of lumped models, that take into account the areal distribution of model characteristics by indicating average values over a series of larger areas that are assumed homogeneous for these characteristics. As a consequence of their nature, physically based models are distributed. Conceptual models can be either lumped or distributed, whilst black-box models are typically lumped.

5.4 Model requirements for the entire Rhine basin

A water management model for the Rhine basin has to meet several requirements. The model must allow the evaluation of hydrological changes in the Rhine basin caused by climate and land use variations. It must be suitable for analysing the changes in total discharge and discharge distribution over the year, as well as changes in height and frequency of discharge peaks. An important factor concerning the model requirements is the large surface area of the Rhine basin. Moreover, the basin includes various types of landscapes, having different hydrological characteristics, and requiring different model concepts. For example, snow storage and snow melt will be most important in the Alpine area, whilst in the lowland area groundwater flow plays a more important role. Several characteristics of the Rhine basin, such as land use and soil type, are at variance on a scale of less than a few hundred meters. Though such a detailed spatial resolution may be obtained in small parts of the basin, on the scale of the entire basin, this would demand huge amounts of data to be collected, resulting in very large data files.

Hydrological models that are used to determine the effect of climate changes on runoff should preferably have a physical basis. A black-box approach is expected to be inadequate for this purpose, because it does not explicitly describe the separate components in the hydrological cycle, and thus does not allow for research of the effect of changes in each of these components under climate changes. In addition, the models can only be calibrated and validated for present-day conditions. Under changed climate conditions, a black-box model may not be sufficiently robust. When using a complex physically based model, comprising all facets of the hydrological cycle, the model parameters are transferable to changed climate conditions. However, major problems are encountered when attempting to use a complex, physically based model. Complex models use a large number of variables, which requires large numbers of data, which usually cannot be easily determined, and which are prone to measurement errors. In addition, model parameters and variables must be considered at the spatial resolution of the model; at this scale, their physical meaning may be different from the point scale. These factors imply that the model will inevitably have to be partly conceptual, while regarding the size of the basin, model lumping may be necessary as well. To enable simulation of both peak flows and low flows, it is important to distinguish between fast runoff processes and slow groundwater discharges. In addition, those components that are affected by changes in land use and climate should be implemented in separate modules. To enable modelling of peak flows of the Rhine, the model must use a time step of one day or less.

5.5 Scale issues

In this study, the effects of climate changes are evaluated for subbasins with very different hydrological characteristics within the larger Rhine basin. This allows for analysis of variations in hydrological response to climate changes within e.g. Alpine areas, lower hilly parts, and lowland areas, as well as their combined effects on the discharge regime in the lower river stretches. A second important aspect of the study is that it enables comparison of model results on different *temporal* and *spatial scales*. Model results obtained using the detailed models on a high temporal and spatial scale can be compared with the results obtained using the coarse RHINEFLOW model. This provides more insight in the demands of hydrological models in assessment studies concerning the vulnerability of river functions in large drainage basins. The results provide a scientific base for the link between macro-scale hydrological models and detailed models in subbasins, and may demonstrate whether macro-scale models can be applied to identify those areas where the hydrological characteristics are most vulnerable to climate changes.

This large-scale project demands a vast amount of data, including geographical, hydrological and meteorological data. In this project, this data has been collected in one single database that is accessible to all project partners.

5.6 General approach of the study

The selection of models and the question of how to couple the models in a consistent way when working on different temporal and spatial resolutions has been solved in the following way. For each of the selected subcatchments a model was chosen and adapted to obtain optimised catchment models with a best fit for each of the selected catchments. All models were physically based but with a varying degree of model detail. Site data (meteorology) was used for catchments; site climate data was compared with CRU baseline climate data to harmonise results. Where possible, all partners tried to use similar data sets (soils, land use, topography), especially where classifications had to be comparable. As it appeared unfeasible to link the models directly in order to build a Rhine model from the aggregated catchment models, a grid-based model was chosen for the entire Rhine basin comprising the selected subbasins of the Rhine. Consistency was achieved by using the same baseline climate as provided by the Climate Research Unit of East Anglia University. The results obtained from the catchments and the Rhine model all tend in the same direction, even if the expression of change differs between the basins as a result of hydrological conditions and influencing factors (e.g. terrain, soils, geology, land use etc.). The uniform trend of the results lends credibility to the chosen scientific approach and also underlines its robustness. An unknown factor is the sensitivity bandwidth of model outputs when the models are applied to different catchments. Scaling has been identified as a key scientific issue in the study, where an approximate solution could be found: e.g. for the catchment scales, the coarse scenario input data had to be interpolated to the catchment scale. Likewise, the re-scaling of monthly data to daily conditions and (as especially in the Alpine region) hourly temporal resolution scales was achieved in an approximate way, bearing in mind the problems of such an approach. In chapter 17, these issues are identified as major research gaps which need further attention in order to arrive at results backed up by an improved scientific basis. Within this general frame, the scientific issues of the different subbasins are outlined in the following paragraphs.

5.7 Scientific issues for the applied models in the subcatchments

Murg, Ergolz and Broye catchments (LHG-IRMB)

In the context of the entire EU project, using a 'bottom-up approach' from the catchment to the Rhine river basin and further on to the EU scale, the three catchments of Murg, Ergolz and Broye are situated at the very beginning in two aspects:

- as small catchments at the lower end of the scale
- as Alpine catchments at the sources of Rhine river.

Therefore the scientific objectives are to model all relevant hydrological processes in a way that guarantees correct results from the climate scenario runs. The relevant hydrological processes in the Alpine environment are the growing and melting of the snow cover, changes in soil water content and evapotranspiration, formation of floods.

The small scale requires a high differentiation of many variables such as soil type, vegetation, land use, land forms as well as a high temporal resolution in the calculations and therefore in the database of meteorological, hydrological and plant physiological data (root depth, leaf area index). Meteorological input data had to be interpolated into a fine spatial and temporal network. This is not an easy task in a mountainous environment: rainfall and wind speed are very unequally distributed, temperature gradients are corrupted by inversions, radiation is very different above and below the cloud-cover. Even in the case of the IRMB-daily-step model, for some data diurnal variations are required.

The quality of the scenarios with its very low temporal and spatial resolution does certainly not match a level like the level of resolution of the observations. Nevertheless it is essential, that the model as well as the input data must attain a very high quality level. Otherwise it would be impossible to separate signals due to climatic change from signals due to data errors, data interpolation errors or model inaccuracy.

Thur catchment (ETH)

The main scientific issues for this Alpine catchment were:

a) a more thorough understanding and the assessment of the sensitivity of the hydrological cycle and of water resources to climatic variations,
b) the development and application of appropriate hydrological models and model components for that purpose.

The combination of high spatial and temporal resolutions, well-adopted interpolation techniques, the use of GIS technologies and physically based process modelling together with a model simulation time of up to 15 years provides favourable conditions for the estimation of the impacts of climate changes on the hydrological cycle. A period of up to 15 years with a resolution of hourly values allows for a statistical analysis of the resulting flow regimes and an estimation of changes in the probabilities of floods and low flows for the 50 year return periods.

The model structure makes it possible to couple the hydrological model with climate and/or groundwater models in order to obtain more realistic hydrological responses to climatic inputs (like climate scenarios). Together with various programs developed for topographical analysis and input data conversion the model packages are ready for applications to catchments and basins with a wide range of geological, topographical and climatological conditions and on different time and spatial scales (ranging from some hectares in 5-minute resolutions up to ten thousands of km^2 in daily or hourly resolutions). The implemented interpolation techniques and runoff generation components enable application in mountainous regions as well as in relatively flat regions (without dominant groundwater flow).

Intensive studies of the influence of altitude on the hydrological components has provided substantial new knowledge with a view to hydrological modelling of high Alpine regions, for example for evaporation estimation. Some scale effects of the spatial resolution on the model results have been investigated (e.g. minimum requirement for spatial resolution for snow cover modelling of around 1000 m × 1000 m).

Mosel and Saar catchments (BfG)

The German portion of the Rhine basin mainly consists of catchments located in the middle mountain range. Though the runoff regime of the Rhine is largely dominated by the Swiss Alps, the middle mountain catchments can play an important role especially during floods.

To study the impacts of climate change within the low mountain range, catchments within the international Moselle river basin (area = 28,152 km^2) were selected. The Mosel is the main tributary within the German portion of the Rhine river basin. Near the city of Trier the Saar (area = 7,431 km^2) and Sauer (area = 4,340 km^2) rivers flow into the Mosel covering 42% of its total area. As representative catchments, the Prüm (area = 891 km^2, Sauer basin) and Blies (area = 1,889 km^2, Saar basin) rivers were chosen.

To enable modelling of the discharge extremes, and in view of the small size of the studied catchments, the model must have high spatial and temporal resolutions.

Overijsselsche Vecht catchment (RIZA)

For the development of a lowland model the catchment of the Overijsselsche Vecht was chosen. This is a small typically sedimentary subbasin, with minor elevation differences, and where groundwater storage is an important factor. The area is mainly used for agriculture, with individual land parcels are only a few hectares in size. These characteristics require that a hydrological model comprises a groundwater component and a good representation of evapotranspiration of different crop types. For an adequate simulation of the discharge, the model must use a daily time step.

Water balance model for the entire Rhine basin (UU)

Within the framework of the research project, the Utrecht University (The Netherlands) investigated the impact of changes in climate on the hydrological regimes of the Rhine and its major tributaries. This subproject formed the link between the studies to the response of water resources to climate changes on the continental scale, carried out by the Institute of Hydrology, and the studies that investigate changes in small catchments, carried out by several other partners.

The objective of the Utrecht University research is to estimate the hydrologic response of the Rhine catchment on a series of different climate change projections. These changes are expressed as changes in average monthly discharges for the Rhine river (160,000 km^2) and its main tributaries (2,000 to 30,000 km^2).

6 Methodological approaches

6.1 General

In view of the complexity of the area and the demands of the model, it was anticipated that the efforts needed to develop a detailed model for the entire basin would be great, and the data requirement huge. Therefore, it was decided to phase the project, and to start by developing a first set of models, following a bottom-up approach as well as a top-down approach. Along the bottom-up line, detailed hydrological models with a physical basis were developed for representative subbasins within characteristic parts of the Rhine basin. The Rhine basin can roughly be subdivided in three more or less distinct parts, the 'Alpine' area, the 'German middle mountains' and the 'lowland' area. The relevant hydrological processes differ within these areas, for example snow melt discharge in mountainous areas versus groundwater flows in the lowlands. The detailed models were considered suitable to analyse the effects of changes in climate and land use for these subbasins on both average and extreme discharges. Along the top-down approach a coarse water balance model for the entire Rhine basin was developed. This model could be used to determine the effects of climate changes on monthly average discharges, but would not provide precise estimates of changes in extreme discharges.

This project demanded a vast amount of data, including geographical, hydrological and meteorological data. For the purpose of the project, this data has been collected in one single database that is accessible to all partners (see chapter 7).

6.2 Methodological approach for the models applied in the subcatchments

Murg, Ergolz and Broye catchments

The hydrology of the three catchments Murg, Ergolz and Broye has been analysed with the same model. These catchments are all situated in the pre-Alpine region of the Rhine basin and have about the same surface area, but their altitudinal distribution is different, and they are situated in different climatological regions with highly varying precipitation amounts. The geological underground varies from catchment to catchment. No major lakes, reservoirs or artificial diversions distort the natural water balance.

The use of the same model for these three basins guarantees that the results are strictly comparable. As one of the catchments, the Murg, is also one of the subcatchments of the Thur modelled by the ETH group, we can even compare our results with the results of the Thur analysis. Thanks to the results of a total of 14 basins, the variety in hydrological behaviour of a large part of the Rhine, in the Swiss pre-Alpine and midland zones, is very well represented. This supports the validation of the results of the next larger-scale model, the RHINEFLOW model.

The aim of the model application is to investigate the changes in hydrological behaviour under climate change scenarios in the Murg, Ergolz and Broye catchments in quantitative terms. The time base of the model calculations comprises a period of several years. Not only for the present climate, but also for the future climate scenarios outlined by the project (see chapter 10), daily values had to be calculated, including several conditional variables, e.g. soil moisture content, snow cover water equivalent versus water flow, evapotranspiration, melt water inflow, and surface runoff.

In order to account for differences in the vegetation cover, the catchment was divided into eight subareas, each representing a particular type of vegetation. For a more detailed estimate of the energy balance of the snow cover, the catchments were divided into several altitudinal slices. Thus daily results on snow cover were available, not only for the catchment as a whole, but also for these different altitudinal slices.

The various parameters were calibrated over a 6-year period. The quality of the model under present conditions was next tested (validated) over another period of about 6 years.

Thur catchment

To estimate the impacts of climate changes on hydrological regimes it is necessary to use, as far as possible, physically based models. By using such models, the uncertainties of model results under climate change conditions will be much smaller than the uncertainties resulting from pure empirically calibrated conceptual models. It is assumed that the basic physical processes do not change, but a change in their relative importance (weight) will occur due to changes in the input data distributions. When introducing physically based process formulations it is necessary to combine them with proper spatial and temporal resolutions. Each physical process has its specific spatial and temporal domain depending on e.g. topography, soil, and vegetation – the 'characteristic' scale.

To meet all the requirements two physically based distributed conceptual model approaches have been set up, both making use of GIS based land surface data:

a) using components already available together with new model components, and aggregating hydrological subareas of similar behaviour (hydrotopes) within subcatchments,
b) a new model version with the spatial differentiation based on a regular grid system, and runoff generation derived from the concept of contributing saturation areas and groundwater runoff.

Therefore, two model versions are now available to deal with the climate-water problem. To be able to include the altitude dependent gradients of meteorological elements (temperature, vapour pressure, wind speed, global radiation, precipitation), interpolation techniques were developed taking into account the topography (altitude, aspect, slope).

In order to be able to give reasonable estimates of climate change impacts, it is necessary to consider a time period as long as possible. The principle of estimating impacts of climate changes is to model a period under present climate conditions and compare the results of this 'control run' with the results of the same model period, but with applied climate change scenarios. By using the time resolution of one hour or one day and a spatial resolution from 100 m to 500 m for the Thur basin (1700 km^2), it was possible to model the present hydrological regime at a high efficiency level. Using the pure grid based model (WaSiM – ETH), statistics of flood and low flows from the control run were compared with results from the various scenario runs. The scenarios, given as monthly changes (percentages or absolute changes in temperature, precipitation, wind speed, radiation and vapour pressure), were applied to the observed climate in combination with both models in a linear way, i.e. the temperatures were increased at a constant rate specified by the scenarios for a full day a.s.o. Changes in hydrological components were then described as changes in flood and low flow characteristics, water balances, flow duration curves, evaporation and groundwater.

Mosel and Saar catchments

The areas of the Prüm and Blies rivers are typical of the low mountain range. In this region, the separation of runoff into surface runoff, interflow and base flow is important. Therefore, the study used a model considering all of these runoff components. As significant groundwater bodies are not likely to occur within the study areas in question, only the unsaturated zone was taken into account. The model used two soil layers representing the rooted zone. A groundwater storage was used to produce a base flow but any groundwater fluxes were not taken into consideration. The rainfall-runoff model was coupled to an evaporation model in order to calculate water balance and runoff for different types of land use for every subcatchment.

The northern part of the Prüm is located in the so-called 'Snowy Eifel' where a significant amount of precipitation falls as snow. Although the snow is usually only stored for a couple of days or weeks, snow accumulation and melt had to be taken into account. For the simulation a daily time step was chosen. Though an exact simulation of peak flows is difficult for small catchments, this temporal resolution is appropriate with respect to the resolution and accuracy of the climate change scenarios.

The scenario application (chapter 10) to the daily data of the present situation was achieved by linear transformation of the mean monthly changes to all meteorological variables. For each meteorological station the values of the grid cell were taken to be the location of the station. The mean size of a grid cell in the study areas was about 1900 km^2 so local conditions could be masked by regional ones. Changes in convective weather conditions were important for the occurrence of summer flood events in small catchments, but they were difficult to indicate.

Lowland model for the Overijsselsche Vecht

For the lowland model a combination of models was used, the hydrological component consisting of a groundwater model, an unsaturated zone model, and a rainfall-runoff model. These were used to compute the daily evapotranspiration and discharge for subbasins. The models were physically based to enable simulation of the effect of changes in climate and land use on different components (e.g. evapotranspiration, groundwater recharge, groundwater flow) of the hydrological system of the lowland part of the Rhine basin. The flow-routing component of the model combines the subcatchments and routes their discharges towards the mouth of the Overijsselsche Vecht. The time step of the model is one day.

6.3 Water balance model for the entire Rhine basin

To estimate the hydrological response of the Rhine and its major tributaries on a series of different climate change projections, the recently developed water balance model RHINEFLOW was used. This model simulates the present and projected discharge in the Rhine basin. The results provide a quantitative measure of the possible response of the Rhine catchment to climate changes. However, as uncertainties surround the magnitude and speed of climate changes in the coming decades, great care should be taken in interpreting the results. This analysis should be interpreted as a sensitivity analysis illustrating trends in runoff and changes in river regime rather than a quantitative prediction of discharge changes in the Rhine in the coming decades.

7. Project database

7.1 Introduction

The development of the RHINEFLOW model and the subcatchment models made it necessary to set up a comprehensive database of topographical, meteorological, hydrological and land use conditions of the entire Rhine basin on a very detailed scale using a Geographic Information System (GIS). The database was also used to refine the scenario simulations. The requirements of the project group supported the establishment of a GIS project group within the CHR with the task to establish a GIS system for the entire Rhine basin with updating and monitoring options. To make results comparable, many efforts were put into e.g. the re-classification of land use maps which appeared differently classified in the participating countries.

The compilation of this most comprehensive database of its kind for the Rhine basin required extraordinary efforts in terms of obtaining, processing and storing the data in a format suitable for use in hydrological models of the entire Rhine basin as well as of subcatchments. Working on the database also revealed the necessity to improve the accessibility and the use of European and national data sets, especially in view of transnational projects with a European dimension. The commercialisation of national services and costing of products proved counter-productive to international research even within the European Union. If all data used had actually been paid for at the costs stated and if all data transfer regulations had been truly followed by the agencies and governmental institutions which supplied the data, research of the kind presented in this report had not been possible.

7.2 Development of the project database

7.2.1 Data collection strategies

The data used in the project was collected by the GIS group of CHR. To acquire the geographical, meteorological and hydrological data, CHR followed two parallel strategies. To begin with, CHR contacted the data providers to supply data for the current research project. Next, CHR aimed at making arrangements with the data providers for the supply of future updates in the desired format. In this construction, CHR functioned as an intermediary between the researchers and the data providers. CHR did not intend to become a data provider itself, it rather intended to be a subscriber of the data needed for its own research. As the CHR members are the national representatives for water management of the riparian states along the Rhine river, many problems with respect to data protection can thus be avoided.

The GIS group of CHR has combined the data from different providers, creating a GIS for the entire Rhine. This GIS is grid-based as well as vector-based, and the data is stored in ARC-INFO format. The vector-based maps have been converted into grid-based maps, containing the same data. These can be used for grid-based models, such as the RHINEFLOW model.

The new data set has not been completed yet. Some geographical data for the Austrian basin section is still missing. For this rather small section, less than 10% of the basin, use was made of the data originally collected by digitising the maps in the CHR atlas of the Rhine basin (CHR, 1976).

Consistency issues

Combining various types of data obtained from several institutes in different countries into one consistent database, and converting these into maps covering the entire Rhine basin was not an easy task. The different countries use various systems to classify their land use and soil type and they have different reference levels for altitude measurements. In the Netherlands and Switzerland water level is referred to as a level in meters above sea level, while in Germany different gauges use different reference levels. With respect to the hydrological and meteorological data, the countries use different procedures to measure various variables. Due to these different procedures or interpretations a number of rather obscure phenomena occur on the borders of different countries. Examples are 100 m^3 water per second in the River Rhine vanishing between Germany and the Netherlands; topographic inconsistencies of several cm to meters appearing at the border between countries, and

Table 7.1 The project data base

Project Database				
Basin	**Thur**	**Murg**	**Ergolz**	**Broye**
Meteorological input data:				
Period	1981-1995	1981-1993	1983-1993	1981-1993
Duration (years)	15	13	11	13
Number of Meteorological stations	18 ... 22	1	1	2
Time resolution	1 h / 6 h	1 h / 1 d	1 h / 1 d	1 h / 1 d
Parameters	T, e, u, G / S	T,Ts,e,u,G / S,Hs	T,Ts,e,u,G / S,Hs	T,Ts,e,u,G / S,Hs
Number of rainfall stations	max. 62	6	13	9
Time resolution	1 d	1 d	1 d	1 d
Source	SMI	SMI	SMI	SMI/SLF
Hydrological input data:				
Period	1981-1995	1981-1993	1983-1993	1981-1993
Duration (years)	15	13	11	13
Discharge stations (number)	12	1	1	1
Grundwaterlevel stations (number)	—	—	—	—
Time resolution	1 h	1 d	1 d	1 d
Source	LHG	LHG	LHG	LHG
Spatial input data:				
Topography:	DEM	map	map	5 zones
DEM-resolution	250 m	—	—	—
Source	L+T	L+T	L+T	L+T
Physiographic characteristics:				
Soil	map1 (1:200 000)	—	—	—
Geology	—	—	—	—
River-network	derived from DEM	—	—	—
Source	GEOSTAT/BFS	—	—	—
Land use:				
Number of types	10 of 35	35	35	35
Space Resolution	100 x 100 m	100 x 100 m	100 x 100 m	100 x 100 m
Source	GEOSTAT/BFS	GEOSTAT/BFS	GEOSTAT/BFS	GEOSTAT/BFS
Hydrologcial model output:				
Flow parameters:				
Interception (I), throughfall (Th)	yes	yes	yes	yes
ET (pot), ET (eff)	yes	yes	yes	yes
Direct (di) and delayed (del) surface flow	yes	yes	yes	yes
Flow of fast drainage deep percolation water	yes	yes	yes	yes
Groundwater flow	yes	yes	yes	yes
Total runoff	yes	yes	yes	yes
Deep percolation	yes	yes	yes	yes
State parameters:				
Snow cover water equivalent	yes	yes	yes	yes
Soil water content: upper and lower zone	yes	yes	yes	yes
Groundwater	yes	yes	yes	yes
Time resolution	1 h	1 d	1 d	1 d
Space Resolution	500 m grid	basin	basin	basin 5 altitude layers

Table 7.1 (continued)

Landquart	**Prüm**	**Saar**	**Vecht**	**Rhine**
1981-1995	1975-1984	1961-1990	1965-1990	1956-1980
15	10	30	26	25
4	3	15	1	27
1 h / 1 d	1 d	1 d	1d	month
T,Ts,e,u,G / S,Hs	T,e,u,G/S	T,e,u,G/S	T,P,e,S,u	T
12	9	65	25	16 (areas)
1d	1 d	1 d	1d	month
SMI/SLF	DWD	DWD/MF	KNMI, DWD	SMI,DWD,BfG,BfL
1981-1995	1975-1984	1961+ /1990	1965-1990	1956-1980
15	10	17 - 30	26	25
5	4	33	28	12
—	—	—	300	0
1 d	1 d	1 d	1d	month
LHG	LfW	BfG/ DIREN/ LfU/ LfW/ SNS	RWS,PROV,SAWA,TNO	BfG,BfL
DEM	Zones within each subbasin derived from DEM	Zones within each subbasin derived from DEM		DEM
25 m	50 x 50 m	30" x 50" (~1 x 1 km)		3 km
L+T	LVA	IfAG/IGN/LVA		Atlas
—	Soil map of Rhineland-Palatinate	Soil map of the EU, soil map of Rhineland-Palatinate	hydrol. unit	FAO
—	Hydrogeological map of River Moselle basin	Hydrogeological map of River Moselle basin	hydrol. unit	-
—	BfG	BfG/LfU	map	generated
—			map	Atlas
7	12	12	12	5
100 x 100 m	30 x 30 m	30 x 30 m	250x250 m	3km
GEOSTAT/BFS	Landsat TM/GEOSPACE	Landsat TM/GEOSPACE	Landsat TM	Atlas
yes	yes	yes	yes	no
yes	yes	yes	yes	yes
yes	yes	yes	yes	yes
yes	yes	yes	no	no
yes	yes	yes	yes	yes
yes	yes	yes	yes	yes
yes	yes	yes	no	
yes	yes	yes		yes
yes	yes	yes	yes	yes (lumped)
yes	yes	yes	yes	yes
1 d	1 d	1 d	1d	month
geometrically homogenous areas	hydrological homogeneous areas within subbasins	hydrological homogeneous areas within subbasins	sub-basin	3km

Table 7.1 (continued)

Legend of parameters:	Legend of Institutions:	
T air temperature	Atlas	CHR/KHR, 1976, Das Rheingebiet. Monographie
Ts soil temperature	BfG	Federal Institute of Hydrology, Koblenz
e water vapour pressure	DIREN	Direction Régionale de l'Environment Lorraine, Metz
u wind speed	DWD	German Weather Service, Offenbach
G global radiation	GEOSPACE	GEOSPACE Satellitenbilddaten GmbH (Consulting), Bonn
S sunshine duration	GEOSTAT/BFI	Swiss Federal Statistical Office, Bern
P air pressure	IfAG	Institute for Applied Geodesy, Frankfurt
Hs snow depth	IGN	Institute Geographique Nationale, Paris
	KNMI	Royal Dutch Meteorological Institute, de Bilt
	L+T	Swiss Topographical Survey, Bern
Footnote	LfU	State Department of Environmental Protection, Saarbrücken
1) storage capacities, soil depth's	LfW	State Department of Water Resources, Mainz
and hydraulic conductivities as	LHG	Swiss National Hydrological and Geological Survey, Bern
qualitative values ranging from 1 to 6	LVA	State Department of Geodesy, Koblenz
	MF	Meteo France, Paris
	PROV	Province of Overijssel
	RWS	Rijkswaterstta
	SLF	Swiss Institute for Snow and Avalanches, Davos
	SMI	Swiss Meteorological Institute, Zürich
	SNS	Service de la Navigation, Strasbourg
	STAWA	Sttatliches Amt für Abfallwirtschaft Münster, Meppen
	TNO	TNO-Delft

winding boundaries between soil and land use types coinciding with national borders, even if both countries use the same classification.

Some of these artefacts, such as the difference in altitude reference level, can be solved rather easily. Others are more difficult to solve. For example: the European soil map forms the basis for soil types in the EU part of the basin. The digital version can be used without any adaptation. For Switzerland we use another database, the so-called Hektaren raster. This database contains a land use classification, giving an indication of the soil types preferably used for different types of land use and leaving it up to the user to choose which soil type is to be attributed to each cell, taking into account other geographical information such as altitude. Another problem arises when a variable, such as land use, is attributed to administrative units, in which case the original data consists of polygons representing these units. The number of square kilometres covered by a certain land use type is specified in these polygons, however, the exact location within the polygon is not known. Since we use a grid-based GIS, this type of information cannot directly be converted into the model database. A last example of a classification that is difficult to compare between countries, is one that gives semi-quantitative interpretations of the intensity of a process. For example an area with serious soil erosion must be interpreted quite differently in Spain when compared with a similar area in Germany.

Table 7.1 summarises the description of the project database.

7.2.2 Description of the database

Digital Elevation Model

The digital elevation model (DEM) is a composite of various databases:

a. DEM of Switzerland
b. DEM of Austria

c. DEM of central Europe (Germany, France, Belgium and Luxembourg)
d. DEM for the Netherlands

a. The DEM of Switzerland is owned by the Bundesamt für Statistik. It is produced from a visual interpretation of the 1:25,000 topographical maps that cover entire Switzerland. These maps were overlaid with a grid with a resolution of 250 m. This 250 m grid is interpolated to a 100 m grid. The cell altitude in this 100 m grid is based on the 16 neighbouring cells from the 250 m grid. The interpolation is carried out with a bi-cubic area function. The accuracy of the original maps is approximately 10 m. This accuracy is reduced due to the interpolation; it is approximately 8 m for the hilly country side and 20 m for the Alpine area.
b. The DEM of Austria is owned by the Bundesamt für Eich- und Vermessungswesen. It is composed by photogrammetrical processing of remote sensing data. The spatial resolution of the database is 50 m. The accuracy is approx. 5 m for open sites and 15 m for afforested areas.
c. The DEM of central Europe is owned by several national Institutes. For this CHR project an excision covering France and Germany has been made. The spatial resolution of the database is 1 square kilometre. The French part of the DEM is derived from the 1:50,000 analogue maps. The maps are overlaid with a grid of 30' × 50' long/lat. For each grid cell the altitude is visually estimated. The work is carried out by the Institut Géographique National (IGN). For Germany the same methodology has been used. Here the work was carried out by the Institut für angewandte Geodäsie (IfaG), Frankfurt a.M.
d. The DEM for the Netherlands originates from a database with one altitude point for every 10,000 m^2. This database has an accuracy of 10 cm. The points are interpolated to a grid of 1 square kilometre, where the average altitude is calculated as the arithmetic mean.

The missing parts of the digital elevation model for the Rhine basin were filled using the European digital elevation model created by the US Geological Survey.

All databases were converted to an ARC-INFO GRID-file in which the window covering the Rhine drainage basin has been cut out. The spatial resolution is one square kilometre.

The altitude reference levels differ from country to country. These range from 27 cm between Germany and France to 231 cm between Belgium and Germany. These differences are small on the scale of the Rhine basin and are not considered relevant for the hydrology on that scale. Therefore no correction has been carried out for these differences.

Soil map

The digital soil map of the Rhine basin is composed of:
a. The digital soil map of Switzerland
b. The Geographical Pedological Database of Europe

a. The digital land use map of Switzerland is based on the analogue 'soil suitability' map, scale 1:200,000 of Switzerland. This map has been scanned and vectorised and consists of 144 units divided over 11,000 polygons. Each soil unit is allocated to a soil type based on the FAO classification by the Landeshydrologie. This vector file has been translated into a grid file of 100 m × 100 m. The owner of this database is the Bundesamt für Statistik in Switzerland.
b. The Geographical Pedological Database of Europe is developed within the framework of the CORINE programme of the EU. It is based on various analogue maps from countries in the EU. The complete database contains 16,000 polygons covering 570 soil units. For this project these 570 units were reduced to 11 soil associations based on the FAO-UNESCO classification. The following associations are recognised: Lithosol, Ranker, Rendzina, Regosol, Fluviosol, Gleysol, Histosol, Cambisol, Luvisol, Podzol, Phaeozem.

The two databases were combined by means of ARC-INFO into a grid with a spatial resolution of 1 square kilometre, and a window covering the Rhine basin was cut out of the database. Since both databases used the same classification, there should be no problems along the boundaries.

Land use map

The digital land use map is composed of:

a. The spatial statistics of Switzerland
b. The land use classification of Germany
c. The land use classification of Luxembourg
d. The land use classification of the Netherlands

a. The spatial land use statistics of Switzerland are collected by visual interpretation of aerial photographs with a stereoscope. For this purpose the photos were covered by a grid representing 100 m × 100 m. Using the elevation map the grid was corrected for differences in altitude. Land use was determined in the bottom left corner of each grid cell. This resulted in a file containing 1 point for each hectare. The file separates 69 land use classes that were aggregated to 15 classes. From the Swiss Geotechnical map the extension of glaciers was determined.
b. The owner of this database is the Bundesanstalt für Gewässerkunde. The land use map of the German and French basin sections originates from a Landsat TM interpretation of the channels 3, 4, and 5. The satellite images were made between 1984 and 1990. The original resolution was 30 m × 30 m which was aggregated to a 1 square kilometre grid. The classification was carried out by GEOSPACE Consult in Bonn. The Landsat survey covers the entire sections except a small section in Sauerland (Germany) that was covered by clouds. The classification used comprises: Built-up area, water, grassland, deciduous forest, Pine forest, mixed forest, Wine yards, fruit yards, sand and dunes, marsh, other types. The land use in one kilometre cell is determined by the majority of land use types in windows of 8 pixels surrounding the central cell.
c. This database is part of the CORINE database, the data is owned by the individual EC members who are also responsible for updates. The database originates from satellite images from Landsat TM which have been verified by field checks. The map scale is 1:100,000. A total of 23 land use classes is distinguished.
d. The owner of the land use classification of the Netherlands database is the Winand Staring Centre. The database is derived from the automatic interpretation of Landsat TM images surveyed between 1992 and 1994, in combination with information derived from aerial photography, topographical maps and agricultural statistics. The spatial resolution is 25 m × 25 m. In the original database 15 classes are distinguished mainly based on different types of agricultural use. The accuracy of the database varies strongly from place to place.

The databases described above were combined and converted into a 1 square kilometre grid. The original classifications were reclassified to a coarser classification that contains the types: Forest, Agriculture and grass, Built-up area and roads, Open water, Glaciers, Bare ground. Some small parts of the Rhine basin are still missing, however.

Water courses

This database is based on:

a. The Hydrological Atlas of Switzerland (Gewässernetz, Schweiz)
b. Digital database containing the water courses in Austria.
c. Digital landscape model of Germany
d. Digital database containing the water courses of France
e. Digital database containing the water courses in Luxembourg
f. Digital database containing the water courses in the Netherlands

Within the framework of the creation of a Hydrological Atlas of Switzerland, the water courses in the Swiss basin section were established by scanning and vectorising the 1990 Landeskarte, scale 1:500,000. In this file the drainage pattern and lakes were identified and several characteristics, such as width, depth and size, were attributed to the polygons and vectors. The accuracy is approximately 100 m as the original maps gave higher priority to the location of the roads than to the location of the water courses. For Austria, the pattern of water courses was digitised on a 1:100,000 scale by the Hydrographisches Zentralbüro (HZB) in Vienna. In Germany, a project that aimed at scanning and vectorising 1:500,000 maps has resulted in a database containing the location and delineation of lakes, rivers and canals. The owner is the Institut für angewandte Geodäsie, Frankfurt a.Main. In Luxembourg, the location of water courses was established by digitising 1:20,000 topographical maps. This database is owned by Ministère de l'Environnement Luxembourg. In France, water courses were digitised from 1:50,000 maps. The first versions were made in 1992 and they are continuously updated. In the Netherlands, this type of information comes from digitised river maps, scale 1:50,000.

Drainage basins

This database consists of the delineation of subbasins which find their origin in the databases mentioned under the caption water courses.

Within the framework of the compilation of the Hydrological Atlas of Switzerland, drainage basins were digitally delineated from analogue maps scale 1:200,000. Basins that were larger than 1000 square kilometre were singled out. These were stored in digital format as a vector format database (polygon files). Owner of the data is the Bundesamt für Landeshydrologie und -Geology. In Austria, the drainage basins were digitised by the HZB in Vienna on a 1:100,000 scale. In Germany, the Institut für angewandte Geodäsie digitised drainage basins from maps scaled 1:1,000,000. In this way the German section of the Rhine basin has been divided into 100 subbasins. These have approximately the same size as the ones distinguished in Switzerland. The delineation of these catchments was compared with the drainage pattern maps and the elevation maps. Based on these last two maps some adaptations were made in the catchment map. This work was carried out by the Bundesanstalt für Gewässerkunde. This database is also digitally stored as a vector database (polygons). The National Geographical Institute of France owns a digital database containing the drainage basins in France. These were established from maps, scale 1:50,000 published in 1992. The information is frequently updated. In the Netherlands, existing maps that show the drainage areas were digitised and stored in vector format.

7.3 Databases for the detailed models of the subcatchments

Murg, Ergolz and Broye catchments (LHG-IRMB)

It is necessary to acquire a large number of different meteorological and hydrological data in high temporal (hours) resolutions over many years to run the IRMB Model (see table 7.1). Another important input in the model is spatial data: land use, different types of vegetation and topography in high spatial (kilometres or 100 m) resolutions are required. All this data has been made generously available free of charge by the authorities mentioned in Table 7.1. We had direct access to the database of hourly climatological data of the Swiss Meteorological Institute.

For use in the IRMB model, all data has been converted into the adequate format. Therefore it is not easily or readily accessible to other projects. Ownership rights regulate the use of the data.

Thur catchment (ETH)

The database for the ETH project consists of climatological, hydrological and geographical data sets. The data used for this project is outlined in table 7.1. The use of all of these data sets is restricted by ownership rights and is subject to the prior permission of the owner in question. Climatological data sets are available at the Swiss Meteorological Survey (SMA, Zurich) and hydrological data sets are available at the Swiss Hydrological and Geological Survey (LHG, Bern). Geographical data sets like land use information, soil characteristics, and digital elevation models are available at the Swiss Topographic Survey (Landestopographie, Wabern) and at the 'Bundesamt für Statistik'.

Moselle and Saar catchments (BfG)

The database for the low mountain range was built up using different types of data:

- Meteorological data

Daily time series of precipitation, air temperature, sunshine duration and radiation, wind speed, and relative humidity from the weather services of France and Germany were taken as input data for the hydrological model. Areal precipitation was calculated using the arithmetic mean of all stations within a subbasin. Each subbasin was divided into elevation zones. Adjustments have been made to the areal precipitation of each elevation zone.

- Discharge data

Discharge data was taken for calibration and validation of the model on a daily basis. The data was delivered by several state and federal river and water resource authorities in France and Germany. Some of the data sets showed significant gaps. These data sets had to be checked and corrected manually.

- Spatial data

Digital and analogue soil maps from different sources were taken to derive soil properties like field capacity, wilting point and infiltration capacity. A digital land use map derived from Landsat TM data was used. For hydrological modelling the following classes have been distinguished: settlements, water, meadow, arable land, deciduous forest and coniferous forest. Digital elevation models (DEM) provided information about elevation zones, mean altitude of each zone and slopes for the Prüm area. Due to the coarse resolution of the DEM for the Saar, basin slopes could not be derived from this source and therefore had to be taken from analogue topographic maps.

Most of the data used for this study is restricted to the project purposes. Additionally to the database for the middle mountain range, a database for the Rhine basin, the RHINE GIS, was built up. The contribution made to this database has been described in paragraph 7.2.

It is important to mention that the data delivered to RHINE GIS is free of proprietary restrictions within the framework of the CHR group.

Vecht catchment (RIZA)

For the lowland model the following types of data were used:

- Meteorological data

Precipitation, temperature, sunshine duration, wind speed and relative humidity are required as input for the hydrological component of the lowland model. This data was obtained from the meteorological station Twente, a station located in the centre of the Overijsselsche Vecht catchment. Precipitation data was obtained from 10 Dutch and 15 German precipitation gauge stations within the Vecht basin. Areal average precipitation of a subbasin is required as upper boundary for the unsaturated zone model and as part of the input for the rainfall-runoff model. The areal average daily precipitation for each subbasin was obtained by Thiessen polygons.

- Daily discharge data

Along the Vecht and its tributaries about 28 gauging stations are located. They are operated by local water boards and regional authorities in the Netherlands and by regional water management agencies in Germany.

- Data on phreatic groundwater levels
- Geographic data on land use, soil-physical characteristics and seepage

Land use data was derived from a Landsat TM image (Zeeman, 1990). Twelve land use classes were distinguished, i.e. potatoes, beets, cereals, maize, grass, deciduous forest, coniferous forest, heather, other nature, urban areas, open water and bare soil. The original 25 m × 25 m pixels were aggregated to 250 m × 250 m cells, using a method that preserves the areal extent of the different land use classes as much as possible (Alewijn and Bakker, 1992).

- Soil physical characteristics

Soil moisture retention and hydraulic conductivity relations are needed as input for the unsaturated zone model. Soil physical units, that are homogeneous with respect to layer structure and soil physical characteristics, were derived from soil maps. Units of the soil maps were converted in representative profiles, which were classified in soil physical units according to the Staring series (Stolte et al., 1991; Wösten, 1987).

- Number of inhabitants of urban areas

This number determines the amount of sewage producing discharge within each subbasin. Except for the Regge basin, the number of inhabitants was estimated using empirical relationships between the number of inhabitants and the size of the urban area.

8 Description of the Rhine basin – regional scale and catchment scale

8.1 The Rhine basin – general characteristics

From an economic point of view, the Rhine is the most important river of western Europe. The course of the river Rhine is 1320 km long. Its drainage basin stretches from the Alps to the North Sea (fig. 3.1.1) and comprises an area of 185,000 km^2. Two thirds of its basin are situated in the Federal Republic of Germany. The Alpine countries, of which Switzerland is the most important, form 20% of the area. More than 50 million people live in the Rhine basin. The river is one of the world's most intensively navigated inland waterways and of major importance for the supply of water to large socio-economically important areas. Changes in the discharge regime can have severe consequences for safety, for the water availability for shipping, industry, domestic use, agriculture, the natural environment and recreational purposes. If possible changes are known, and the sensitivity of the main river functions can be assessed, then counter measures can be formulated to minimise negative effects of climate changes.

Geography and geology

On the basis of its geographical and climatological characteristics, the Rhine basin can roughly be subdivided into three parts: the Alpine area upstream Basel, the German middle mountains between Basel and Köln, and the lowland region.

The Alpine mountains comprise more than 16,000 km^2, with maximum elevations of more than 4000 m a.s.l., about 400 km^2 of which are covered with glaciers. The upper stretch of the Rhine from its source to the Bodensee is called the Alpenrhein. The stretch between the Bodensee and Basel is called Hochrhein. The main tributaries in this area are the Aare, Reuss and Limmat rivers, which drain the highest parts of the area, the Thur, and the Broye.

The German middle mountains consist of the Vogesen and Schwarzwald in the south, the Schwäbische and Fränkische Alb along the eastern boundary of the basin, and the Rheinische Schiefergebirge in the central-northern area. Maximum elevations range from more than 1000 m a.s.l. in the south to around 600 m a.s.l. towards the north. Average elevations vary from 200 m to 400 m a.s.l. The Rhine between Basel and Bingen is called the Oberrhein. The deeply incised river stretch across the Schiefergebirge down to Köln is called the Mittelrhein. The main tributaries within the middle part of the basin are the Neckar, Main, Moselle, Lahn and the Sieg.

The lowland part includes extensive sedimentary areas, including loess, (fluvio)glacial deposits, cover sands, and fluvial deposits of the lower river Rhine delta. The main tributaries are the Lippe, Ruhr, and the Vecht. Within the Netherlands the Rhine splits up into three main distributaries: the Waal, Nederrijn-Lek, and IJssel.

Climate

Climatic characteristics of the basin vary considerably for the three major parts of the basin.

- Within the Alpine area, large differences in precipitation occur, associated to both orographic and convective precipitation. Maximum annual precipitation in the mountains can be as much as 3000 mm, whilst in valleys at the lee side annual precipitation is only 600 mm. A substantial part of the precipitation is temporarily stored in a snow cover.
- Within the middle mountain region, climate parameters and their spatial variability are largely determined by the site elevation. Whilst average temperatures decrease with elevation, high temperatures occur on sheltered valley slopes. Precipitation generally increases with elevation, with considerably larger annual precipitation at the west-exposed sides of mountain ranges, and low precipitation at the lee sides. Within the southern part, high amounts of rainfall especially occur at the western flank of the Vogesen. During the summer period, convective precipitation is important within the lower areas. When accounting for altitude, average precipitation decreases from north to south.
- The climate of the lowland part is maritime in character, with a lower annual and daily amplitude of temperature than the upstream part of the basin. Precipitation is mainly governed by the passage of frontal zones.

Hydrological regime

The discharge of the Rhine river is mainly determined by the amount and timing of precipitation, snow storage and snow melt in the Alps, the evapotranspiration surplus during the summer period, and changes in the amount of groundwater and soil water storage. The Alpine rivers are governed by a snow melt regime, with a pronounced maximum in summer. This maximum is generated by storage of precipitation in the snow cover in the winter, and its melting in spring and summer, amplified by summer rains. There is a slight decrease in the summer maximum which is caused by reservoir storage of 1.9×10^9 m^3, taken in summer and consumed in winter for power production. Retention of water in the Alpine border lakes has a smoothing effect on the Rhine discharge fluctuations. Groundwater recharge is less important in the Alpine area because the volume of unconsolidated sediments, potential aquifers, is small. Downstream of Basel, the pluvial regime gradually starts to dominate the Rhine discharge. At the Mosel confluence, the discharge maximum is moved to the winter season, maintaining however a considerable discharge in summer from the Alpine region. In dry periods, like the summer of 1976, the discharge ratio from the Alps can be as high as 95% (CHR, 1983). The summer discharge minimum in the central and lowland areas is due to high evapotranspiration during the growing season exceeding the contribution of precipitation to the runoff, in spite of the precipitation maximum in the summer period. During the winter half-year, precipitation in the lower parts of the basin predominantly falls as rain, and any snowfall usually melts quickly. Going further downstream, the declining contribution of the tributaries to the mean annual runoff is mainly due to the regression of precipitation in the lower parts of the basin.

Functions of the Rhine

The most natural function of the Rhine is to discharge water, sediment and ice. The average discharge at the German-Dutch border is about 2300 m^3/s. Each year, the Rhine carries about 400,000 m^3 of sand and gravel, and about 2,000,000 m^3 of suspended solids.

Safety

To protect the low hinterland along the river, embankments have been built along the river. In the lower part of the basin, almost the entire river stretch is bordered by river dikes. For the safety of the hinterland, the discharge capacity of the winter bed of the river should be adequate to carry large amounts of water during flood periods. Safety standards, expressed in terms of failure probabilities are used as a measure for the dimensions of the embankments. For example in the Netherlands, this 'failure probability' is set at 1/1250 per year.

Water supply

The Rhine water itself is used for various purposes. In the Alpine area, large amounts of water (up to 1.9×10^9 m^3) are stored in reservoirs for power generation. Along the middle and lower stretches of the Rhine, the water is also used for power generation. In Germany, considerable amounts of water are diverted from the Rhine into navigation canals. The Rhine is an important source for drinking water, for industrial use, and, in the river delta in the Netherlands, for flushing the polders, and preventing the intrusion of salt from the North Sea. Rhine water is also used as cooling water for industry and power plants. In times of drought, the agricultural and horticultural sectors use Rhine water for irrigating crops and as drinking water for live stock.

Inland navigation

The Rhine is the most important waterway for inland navigation. Inland shipping along the Rhine plays a dominant role in the international transport of goods in western Europe. In the Netherlands, the Waal distributary is the most important route, thus being the busiest river in western Europe. The number of ships passing Lobith amounts to 170,000 a year. By using ever larger ships, such as four-barge and six-barge push-tows, collective loading has been on the increase, while the number of ships remains the same. In 1990, total transport volumes on the Rhine at Lobith amounted to 143 million tonnes. For the forthcoming decades a substantial growth of transport via inland navigation is anticipated.

Fig. 8.1 The Rivers Rhine and Mosel at Koblenz (top) and a view of the narrow lower Mosel valley (bottom)

Ecological functions

The ecological value of the river Rhine has been the focus of increasing attention in recent years. The river and its floodplains form an important interconnected network that provide ecological corridors for plants and animals. In this respect it is worth noting that the water quality of the Rhine has improved considerably over the past decades. In the context of ecology rehabilitation projects, opportunities are being created for the return of plant and animal species that lived in and around the river in large numbers before mankind intervened.

8.2 Selected catchments in the Alps

Murg, Ergolz and Broye catchments

The three basins outlined amongst others in figure 8.2.1 have been chosen for the model experiments with the IRMB model. The selection of these basins among the many research basins of the Swiss Hydrological and Geological survey has been based on different grounds: (1) for a daily step model, the basins have to cover a certain minimum area; (2) the basins are well equipped with dense networks of rain gauges and with automatic climatological stations of the Swiss Meteorological Institute that is able to fulfil the data requirements (see figure 8.2.1 and table 7.1); (3) the basins are geologically well defined; (4) the hydrology in the basins is only marginally influenced by man, population is not dense; (5) there are no lakes, no important water diversions nor any reservoirs in it; (6) the type of hydrological regime is 'pluvial' for the greater part of the three basins; (7) the altitudes of the basins are not excessively high so that additionally important problems such as snowfall, snow cover or even glaciers are avoided.

The Murg is a tributary of the Thur which in turn flows into the Rhine (see figure 8.2.1). Its basin gives a good representation of the landscape and – with 1220 mm precipitation per year – the hydrology of the foothills of the east-

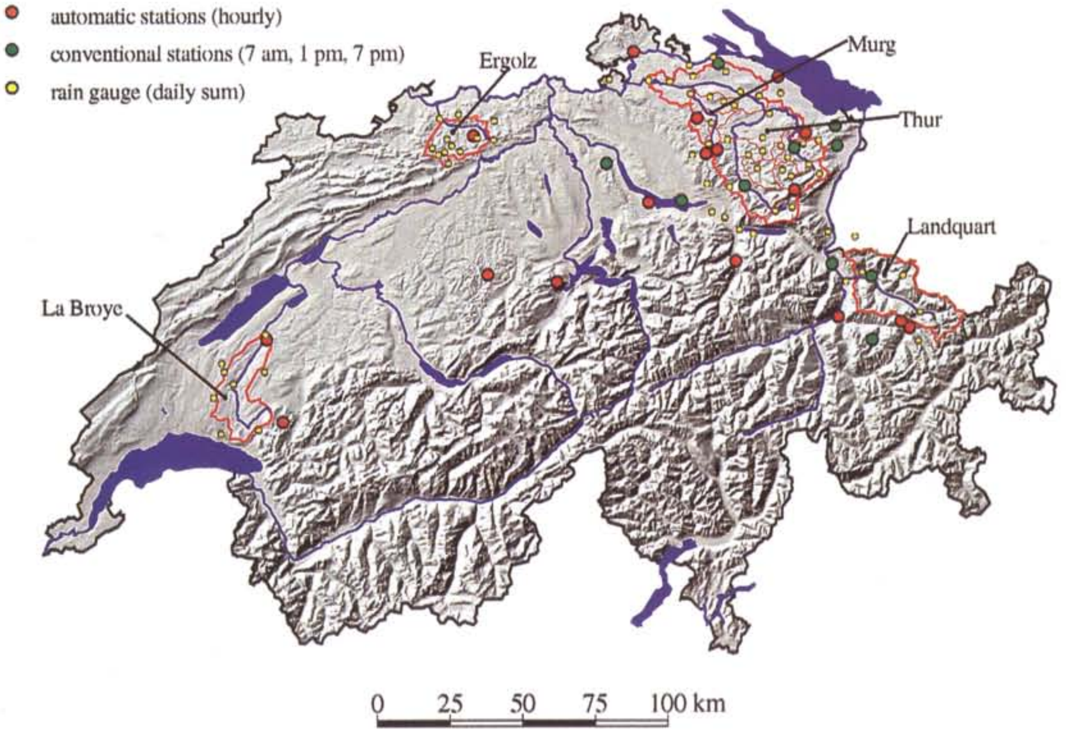


Figure 8.2.1 Location of the Thur, Murg, Ergolz, Broye and Landquart river basins in Switzerland; red polygons: delineation of basins and subcatchments; red, green, and yellow dots show the locations of meteorological stations used for this study.

Figure 8.2.2 The Murg basin

Figure 8.2.3 The Ergolz basin

ern Swiss lower Alps. The upper part is mostly covered by forest and pasture (figure 8.2.2) while in the lower part intensive agriculture is predominant. From a geological point of view, the basin is located in an area of molasse with alternating layers of conglomerate, marl and sandstone, partly covered by moraines. The lower sides of the valley and the valley floor have been flattened out by alluvial deposits of high permeability. In this part of the basin, the only groundwater zones are found. From and into these zones some groundwater may flow across the boundaries of the basin.

The *Ergolz* drains directly into the Rhine. It represents the typical characteristics of the Jura mountains (figure 8.2.3), although at only 1080 mm annual precipitation is at the lower end for the Jura range. Land use is similar to that of the Murg basin, but while the Murg basin

Figure 8.2.4 The Broye basin

is largely covered by coniferous forests, the soil developed on limestone in the Ergolz basin primarily accommodate deciduous forests.

As far as geological aspects are concerned, it is important that this basin is located in the Jura area. Owing to the karstification of the limestone bedrock, drainage routes cannot always be located exactly. Like other karst areas, the Jura mountains are characterised by a widespread absence of surface runoff, the presence of enclosed compressions and the common occurrence of caves and other large subsurface conduits. The bedrock permeability of the Ergolz basin is, however, strongly reduced due to interbedded marls.

The *Broye*, situated in the western part of the Swiss midland, runs into the Murten lake and further downstream into the Aare river, the main tributary to the Rhine in Switzerland. This basin is the highest of the three basins, its top being at 1514 m a.s.l. (see table 8.2.1). However, only 5% of the basin area is higher than 900 m a.s.l. This part is covered by coniferous forest and pasture. In the wide valley land is used by intensive agriculture. In this lower part (figure 8.2.4), irrigation is often necessary for two reasons: (1) precipitation in the valley amounts only to around 850 mm due to the shielding effect of surrounding hills and (2) the presence of alluvial deposits of high permeability in the bottom of the valley.

Still, the greater part of this basin accounts for the drainage of part of the Molasse Plateau which essentially consists of very low permeability detrital formations of Oligocene and Miocene ages. Most of its surface is covered by generally even less permeable Pleistocene tills, gravely sands and silts, which however locally form important groundwater reservoirs.

The Landquart catchment

In order to investigate climate change processes in higher Alpine environments, the Landquart basin was selected from the many basins in the Alps mainly for three reasons: (1) the basin is well equipped with four climatological stations, from the bottom of the valley up to the Weissfluhjoch at 2450 m a.s.l., where the Swiss Institute for Snow and Avalanche Research has its laboratories; (2) in the Alps no medium size basins can be found that are not influenced by the diversion of water for hydroelectric power generation. This also applies to the Landquart basin, however diversions have been meticulously measured for a long period of time. In this way it is possible to calculate the natural runoff in the Landquart river, at least for daily mean values. (3) The type of hydrological

Figure 8.2.5 The Landquart basin

regime is changing from 'glacio-nival' to 'nival-alpine' (Weingartner und Aschwanden, 1993) going downstream the river. Consequently, snow cover and snow melt are important elements in the hydrological cycle, but glaciers do not play a dominant role.

The Landquart basin is situated in the eastern part of the Swiss Alps. The Landquart river is a tributary to the Alpine Rhine, the section of the Rhine running into Lake Constance. Annual precipitation amounts to 1670 mm and a liquid water regime occurring almost only in the March-October period. Slopes are steep and about 25% of the area is composed of rocks, glaciers, moraines, debris and detritus without any vegetation (figure 8.2.5). A large portion is pasture (see table 8.2.1). Only a small portion is used by agriculture.

This drainage basin covers a tectonically complex area extending across the boundary between the Penninic and the Austroalpine nappes. The Penninic nappes, located in the western part, mainly consist of Bündnerschiefer (metamorphic shales and impure limestones – calcschists) and Prättigau Flysch (alternation of shales, sandstones and detrital limestones, with intercalations of polygenic breccias), both of which have a very low permeability. The Austroalpine nappes in the eastern part of the basin are built up of gneisses, micaschists and amphibolites with mdium to low permeabilities.

Thur basin

The Thur basin is located in the North-East of Switzerland (see figure 8.2.1). The lower and middle regions are characteristic of the Swiss lower Alps with respect to topography, climate, and land use, whereas the upper parts show high alpine climatic and land use characteristics (see also figure 8.2.6). The Thur basin extends over an area of around 1,700 km^2. The head waters of the Thur river find their origin in the alpine, southern part of the basin. After 127 km stream length it is the first major tributary of the Rhine downstream Lake Constance. The proportion of area below 1,000 m a.s.l. is around 75%; only 0.6% (10.2 km^2) is above 2,000 m a.s.l. The Thur basin is free of glaciers, although there are some perennial snow fields with a total of around 0.1 km^2. Table 8.2.1 summarises the characteristics of the Thur basin in coparison to the other Swiss basins of this project. There are neither major natural nor artificial lakes or reservoirs. Besides the settlements, the influences of human activities on hydrology are considered to be rather small. The basin is very well equipped with meteorological and hydrological gauging stations.

Table 8.2.1 Characteristics of the catchments in the Alps

Basin	Thur	Murg	Ergolz	Broye	Landquart
Gauging Station	Andelfingen	Frauenfeld	Liestal	Payerne	Felsenbach
Area (km²)	1700	212	261	392	616
Lowest point (m a.s.l.)	356	390	305	441	571
Mean altitude (m a.s.l.)	769	580	590	710	1800
Highest point (m a.s.l.)	2504	1035	1169	1514	3244
Slope angles (degrees)					
Lower parts	3	–	–	–	–
Upper parts	20 (max. 65)	–	–	–	–
Mean slope angles	9	4	9	5	21
Land use in %:					
Agricultural crops and meadows	52	62	51	67	13
Pasture	9	0	4	2	40
Forests, shrubs	29	29	40	25	23
Settlements	8	8	5	5	1
Water and rocks	2	1	0	1	22
Glaciers/perennial snowfields	< 0.1	0	0	0	1
Water balance:					
Precipitation (mm/a)	1450	1220	1080	1300	1670
Runoff (mm/a)	900	620	440	590	1220
Evapotranspiration (mm/a)	550	600	640	710	450

The geology and pedology in the south-eastern part of the Thur basin – the higher alpine part – are characterised by limestone and shallow soils or rock areas bare of soils. In this region karst-hydrologic effects are widespread. The shallow soils with less water storage capacity lead to fast discharge responses on rainfall events, slightly dampened due to karst hydrologic properties. There can be considerable loss of water due to karst caves draining this part of the Thur basin also to the South and East into neighbouring basins.

The main part of the Thur basin belongs to the conglomerates, marls and sandstones of the 'Mittelländischer Molassetrog', characterised

Figure 8.2.6 The alpine part of the Thur basin near Stein/Thur gauge

by low hydraulic conductivities and medium to high water storage capacities. The middle and lower parts of the basin are partly covered by moraine sediments characterised by medium to high hydraulic conductivities and high water storage capacities. In the valleys of the lower Thur and its main tributaries, fluvial gravels were deposited. Major groundwater resources can be found in these valleys as well as in the moraine sediments.

8.3 Catchments in the middle mountain area

Prüm catchment

The selected study catchments represent different parts of the Mosel river basin. The Prüm river basin belongs to the Rhenanian schist mountains whereas the Blies river is situated in the Pfälzer Bergland and the Buntsandstein of the Haardt.

Representing the Sauer river basin, the Prüm river ($A = 891\ km^2$) as a main tributary has been chosen as study area. The Prüm originates from the Steinberg near the City of Ormont at an altitude of 636 m a.s.l. taking up some smaller headwaters flowing from the Schnee-Eifel. Its course of 88 km length is mainly directed north-south in the upper part, turning to south-east in the lower section. At the headwaters, the valley is wide and flat. A winding, narrow, deeply incised section is found where the Prüm approaches the Sauer river at 152 m a.s.l.

Geologically speaking, the basin consists of devonian schists and slates of very low permeability forming the northern part of the basin. The soils are characterised by low infiltration capacities and cause a high portion of direct runoff. In the Trier triassic basin, situated in the south, sandstones as well as claystones with limestones, marls, and marly limestones are found. Karst effects do not occur within the Prüm basin except for some known areas situated on the Nims river, a tributary to the Prüm.

In hydrological terms, the Prüm can be characterised as a quick responding catchment with a high percentage runoff. In winter times, a certain amount of precipitation falls as snow. Although precipitation is distributed more or less uniform over the year with a maximum in December and a second maximum in June, the ratio of summer runoff to winter runoff is 0.33 and thus low. Besides other factors, this can be explained by the land use distribution. A significant part of the basin is used as arable land and meadow. In relative terms, the forested portion is small and concentrated on the hill slopes not particularly suited for agricultural use.

Figure 8.3.1 Impressions of the Prüm river catchment near Prümzurlay

Figure 8.3.2 The Saar river near Völklingen

Contrary to other portions of the Sauer river basin, the network of gauging stations with respect to long-term observations is favourable (see chapter 7). Beside the Sauer river basin, the landscape and hydrology of the northern Mosel tributaries are also represented. In table 8.3.1 the basin characteristics are summarised.

Saar catchment

The Saar river basin is shared by France and Germany, each accounting for about half of the basin area (52.6% and 47.4%, respectively). Its main tributary, the Blies river (catchment area = 1889 km^2), doubles the catchment area at

Table 8.3.1 Basin characteristics for catchments in the low mountain range

Basin	Sauer	Saar
Subbasin	Prüm	Blies
Gauging Station	Prümzurlay	Reinheim
Area (km^2)	574	1798
Lowest point (m a.s.l.)	150	205
Mean altitude (m a.s.l.)	435	330
Highest point (m a.s.l.)	700	545
Land use in %:		
Settlements	5	6
Meadow and pasture	38	27
Agricultural crops	17	14
Deciduous forest	14	35
Coniferous forest	17	15
Mixed forest	2	3
other use	7	-
Long term water balance:		
Precipitation (mm/a)	900	930
Runoff (mm/a)	440	340
Winter (mm/a)	330	215
Summer (mm/a)	110	125
summer runoff to winter runoff (%)	0.33	0.58
Evaporation (mm/a)	460	590

the French-German border near Sarreguemines. Like the Saar, the Blies partly belongs to France.

The headwaters of the Blies originate near Birkenfeld 380 m.a.s.l. At the town of Einöd, the main tributary, the Schwarzbach is taken up, a river exceeding the Blies in size as well as runoff. After a river course of nearly 100 km, the Blies falls into the Sarre river near the city of Sarreguemines.

In geological terms, the Blies catchment is mainly formed by the triassic formations of Red Sandstone, Muschelkalk, and Keuper. Generally speaking, they occur sequentially from the north-east to the south-west. Although the soils are mainly of intermediate permeability, some parts within the limestone regions of the Muschelkalk are areas of high permeability.

Compared to the Prüm, the runoff regime is slightly different. A smaller amount of water runs off, and evaporation is significantly higher. This is mainly caused by a different land use distribution. The landscape is dominated by forests which cover more than 50 percent of the area. There are also differences in the annual runoff distribution. Relative to winter runoff, the amount of summer runoff is higher. It should be noted that during dry periods water from the Nonnweiler reservoir at the neighbouring Prims river may be transferred to the Blies river, thus raising the latter's water level.

8.4 Lowland area

Overijsselsche Vecht catchment

The Overijsselsche Vecht is a rain-fed river with a catchment size of 3800 km^2, a length of 177 km, and a total elevation difference of 106 m. About 1800 km^2 is located in Germany; the remaining part of the drainage catchment is situated in the Netherlands. The river rises in the Baumgebirge in Nordrhein-Westfalen. Contrary to the rest of the catchment, the gradient of the river is relatively steep in this upper part. About two-thirds of the total elevation difference are bridged here, along only 25% of the river's total length. The main tributaries in the German part are the Steinfurter Aa and the Dinkel. In the Netherlands, the main tributary is the Regge.

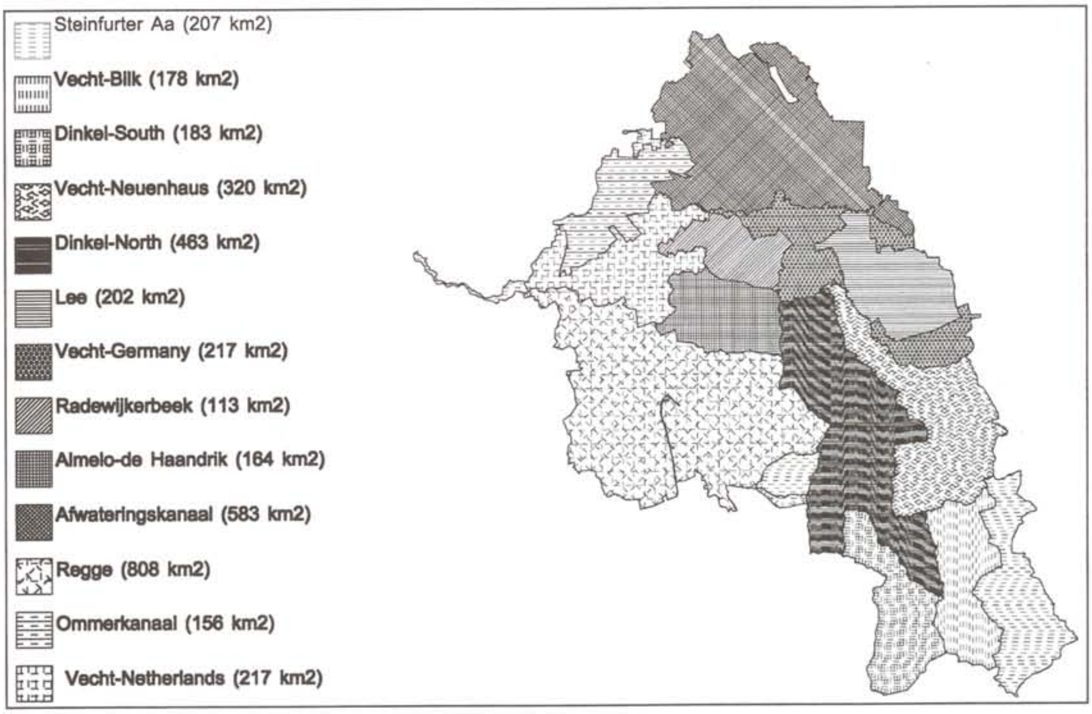


Figure 8.4.1. Catchment of the Overijsselsche Vecht: subcatchments and main water courses. North is up. The N-S distance is about 100 km, E-W is about 75 km

Table 8.4.1 Characteristics of the daily discharge (in m³/s) of the Vecht, Meuse and Rhine rivers, for the 1975-1990 period

river, station	area (km²)	Q_{min}	$Q_{5\%}$	$Q_{50\%}$	$Q_{95\%}$	Q_{max}	$(Q9_{5\%}-Q_{5\%})/Q_{50\%}$
Vecht, Vechterweerd	3,800	2.7	5.3	24.2	114.4	311	4.6
Meuse, Borgharen	33,000	0	12	163	809	2466	4.9
Rhine, Lobith	165,000	782	1067	2067	4832	10274	1.8

The Vecht catchment can be subdivided into 13 subcatchments. Seven subcatchments in the German and six in the Dutch part of the catchment. In figure 8.4.1 the watersheds of the subcatchments are given. The area of the subcatchments varies between 100 and 800 km², the average size is about 300 km².

The soils in the southern part of the catchment are mainly sandy-loam, and in the middle part mainly sandy. In the northern part excavated peat soils are found. Near the rivers, clay has been deposited and locally glacial till layers are present in the subsoil (Stolte and Wösten, 1991). The subsurface and the shape of the catchment have largely been determined by the Saalien ice-age in which land ice covered the northern low land area of the Rhine basin. In the Saalien period ice-pushed ridges were formed that are still present in the landscape, and glacial till was deposited in the river valleys. In the last ice-age, the Weichselien, large bodies of wind-borne sands were deposited. Swamps and moors developed at places were water stagnated due to the glacial till layers. Since the Middle Ages the development of the Vecht catchment has largely been determined by human influence. Moors were excavated and channel networks were constructed to transport the excavated peat. The remaining sandy soils were used for agriculture. At present about 75% of the land is used for agriculture, 20% for forest and other nature and 5% is urban area. The urban area has increased strongly in the last decades. To date, about 1.2 million people live in the Vecht catchment.

Average annual precipitation is about 780 mm. Annual evapotranspiration is on average about 490 mm. The discharge regime is highly variable, due to the rain-fed character of the catchment. For comparison, the same characteristics are also given for the rivers Rhine (a combined rain and meltwater-fed river) and Meuse (a rain-fed river). The variability of the Vecht and Meuse is indicated by the relatively large difference between the 5% and 95% discharge compared to the 50% discharge.

The Vecht catchment can roughly be subdivided into three parts:

1. Subcatchments in Nordrhein-Westfalen

Figure 8.4.2 The Vecht river

(German part), including Steinfurter Aa, Vecht-Bilk and Dinkel-South. These catchments are relatively hilly, and groundwater flows play a minor role in the discharge processes. Groundwater levels are shallow in the stream valleys, and deep on the hilly parts. The major part of precipitation is rapidly discharged to the surface water, resulting in a short reaction time of the tributaries to rainfall. There are no large urban areas, only a few small towns.

2. Subcatchments in Niedersachsen (German part), comprising Vecht-Neuenhaus, Dinkel-North, Lee and Vecht-Germany. Here, the groundwater component plays a more important role. Besides some small towns there is a large urban area in the Dinkel-North subcatchment.
3. Subcatchments in the Netherlands. These have more or less the same characteristics as the subcatchments in Niedersachsen. The drainage and water management system is however much more complex. In two subcatchments, Regge and Afwateringskanaal, large urban areas occur. For these subcatchments, waste water is an important part of total discharge in dry periods.

In the entire Vecht catchment, land use is mainly agricultural, with grass and maize as major crops.

9 Development and description of the hydrological models

9.1 Summary

Baseline for the model development has been the focus on application of existing models to the climate change scenarios rather than the development of entirely new models. Thus, existing models have been adapted to best-fit conditions of the catchments. All models were physically based, though with a varying degree of detail. The model concepts and performances had been proven in earlier applications so that the strength and weakness of each model was known prior to the selection of the models for the purpose of this study. Scale issues were debated throughout the selection process: Models used in alpine and pre-alpine catchments were tailored to be used on an hourly up to daily time scale, the model used for the central part basins (Prüm, Blies, Saar) is a model running on a daily time scale. The RHINEFLOW model used for the entire basin is relatively coarse with a resolution of 3 × 3 km and operates on a monthly time scale which makes it scale-compatible with present GCM outputs and the resulting climate change scenarios. The link between the models has been the use of a common baseline climatology and the comparison of results obtained from the RHINEFLOW model with the results obtained from catchment models. Table 9.1 below summarises the models used. The following paragraphs give a more detailed description of the models.

9.2 Description of the models

9.2.1 The IRMB model for Murg, Ergolz, Broye

The IRMB model, for **I**ntegrated **R**unoff **M**odel – F. **B**ultot, is a daily conceptual hydrological model (Bultot and Dupriez, 1976a, b, 1985). It has been devised by the Hydrology Section of the Royal Meteorological Institute of Belgium to simulate the components of the water cycle in medium-sized catchments, i.e. basins for which the input data, and in particular rainfall, can be considered 'uniform' (surfaces ranging from 200 km^2 to 1500 km^2).

The IRMB model is based on a cascade of subreservoirs representing the various main water storages of the catchment and the transfers

Table 9.1 Model selection and climate change scenarios

MODEL SELECTION AND APPLICATION	CLIMATE CHANGE SCENARIOS
Utrecht: RHINEFLOW model: Conceptual water balance model	Application of scenarios: Adjust a local time series using GCM scenario changes
BfG: HSPF model, a semi-distributed conceptual model	
LHG: IRMB-model (modified), detailed conceptual model	DISSEMINATION OF CLIMATE DATA: From the CRU through the Institute of Hydrology (IH): – Gridded Baseline Climatology Data – Gridded Equilibrium GCM Data – Gridded Transient GCM Data
ETH: two models: – Distributed, physically based: PREVATH model – Grid-based model (WaSiM - ETH)	
RIZA: Actual evapotranspiration: MUST (unsaturated zone model), physically based; Discharge: Conceptual rainfall-runoff model; Seepage: Physically based steady-state groundwater model	

between them. It provides estimates of: (i) water transfers (throughfall, effective evapotranspiration, surface runoff, infiltration, deep percolation, etc.); (ii) the various state variables of the water cycle (water equivalent of snow cover, water accumulated in the vegetative canopy and on the ground surface, water content of the aeration zone and of the saturated zone of the soil, etc.); (iii) flows at the outlet of the catchment (surface flow, baseflow, interflow and alluvial-zone flow).

The main climatological input data is areal precipitation and potential evapotranspiration. The latter is calculated for each vegetation cover by the energy balance method (Bultot et al., 1983), which involves several climatological variables: net radiation, air temperature, atmospheric water vapour pressure, soil temperature at depths of 10, 20 and 50 cm and wind speed 2 m above the ground. Most of these data is also used for calculating the snow water equivalent. For the air temperature and the atmospheric water vapour pressure, which both depend on advection phenomena rather than on the morphological features of the plant cover, identical areal mean values have been adopted for all types of cover.

The surface of the catchment is divided into eight subareas, each representing a particular type of cover. Besides impervious areas, seven types of natural covers are considered, i.e. deciduous forests, coniferous forests, pastures, winter cereals, spring cereals, maize and beets. The model is devised so that each type of cover is individually characterised by: (i) its own area; (ii) the relationship used for estimating how much rainfall is intercepted by the vegetative cover (e.g. leaf area index given by Von Hoyningen-Huene (1981)); (iii) the maximum available water capacity of the soil (i.e. field capacity minus storage capacity at wilting point for a given root zone depth); (iv) the albedo used for the calculation of the energy balance of the surface. The values of the last three quantities vary in the course of the year, following the annual cycle of plant growth.

The water content of the upper part of the aeration zone of the soil is an important parameter estimated using the observed surface flow. It determines the throughfall absorbed by the soil before any surface runoff can appear. After saturation, the routing of the surface runoff is managed by seasonal unit hydrogrammes determined on the basis of the calibration period. As the model has been usually used to estimate the catchment's water balance, the procedure of optimisation of the model parameters has not been focused on particular flood events but on periods including high and low stages. Low stages are important to establish the recession of the groundwater storage and thus the water resources of the basins.

The complete flowchart of the IRMB model has been given in figure 9.2.1. In the upper part of the model, each of the eight cover types is handled separately. Daily estimates of interception, throughfall, evapotranspiration, surface runoff and percolation processes are thus obtained for each type of cover. Possible interactions between runoffs beneath various covers cannot be accounted for. Areal means of the daily values are then used to determine basin-wide estimates of the values of surface runoff and deep percolation, as well as of the evapotranspiration and of the various state variables of the water cycle.

In such a structure, where a one-to-one relationship has been established between each vegetative cover and its parameters, the model is particularly suitable for assessing possible impacts of modifications of the vegetative cover by mere reference to the weighting coefficients of the different cover types.

The main development carried out for this study concerns the snow cover simulation. The Broye catchment is located in the range of medium alpine altitudes. The highest part of the catchment reaches heights close to 1500 m, that corresponds to a strategic range of altitudes for tourism and, in particular, for skiing activities. The study of the snow accumulation and melting processes in this catchment has justified the development of new algorithms taking into account a more detailed estimate of the energy balance of the snow cover. Due to the length of the catchment and the altitude difference between the outlet and the upper part of the catchment, there is a strong precipitation gradient, combined with the orographic temperature gradient. In order to tackle these inhomogeneities,

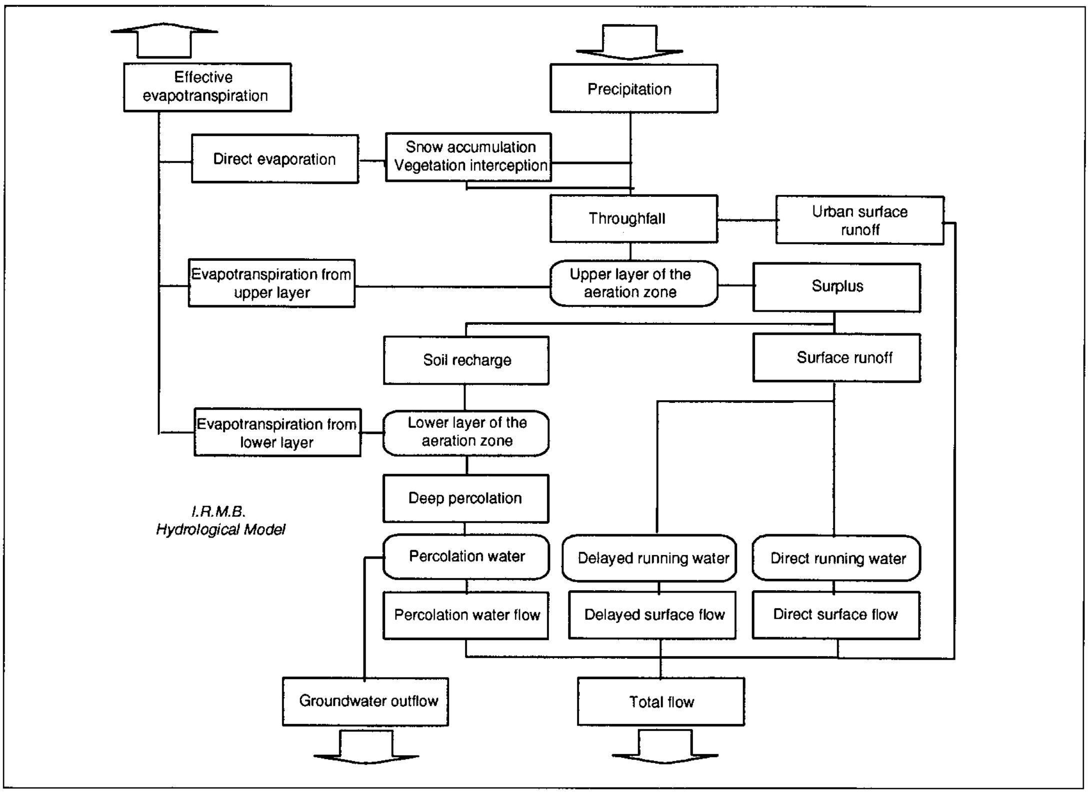


Figure 9.2.1 Flowchart of the IRMB model

areal precipitation on subareas has been introduced, allowing higher snow precipitation in the upper zones than in the lower ones. Under particular weather conditions, this also allows for snow melting in the lower part of the basin and snow accumulation at the top. The subarea precipitation amounts adopted correspond with Thiessen's estimates over five altitude 'slices'. The full description of the equations and of the results of the simulations are presented and discussed in Bultot *et al.* (1994).

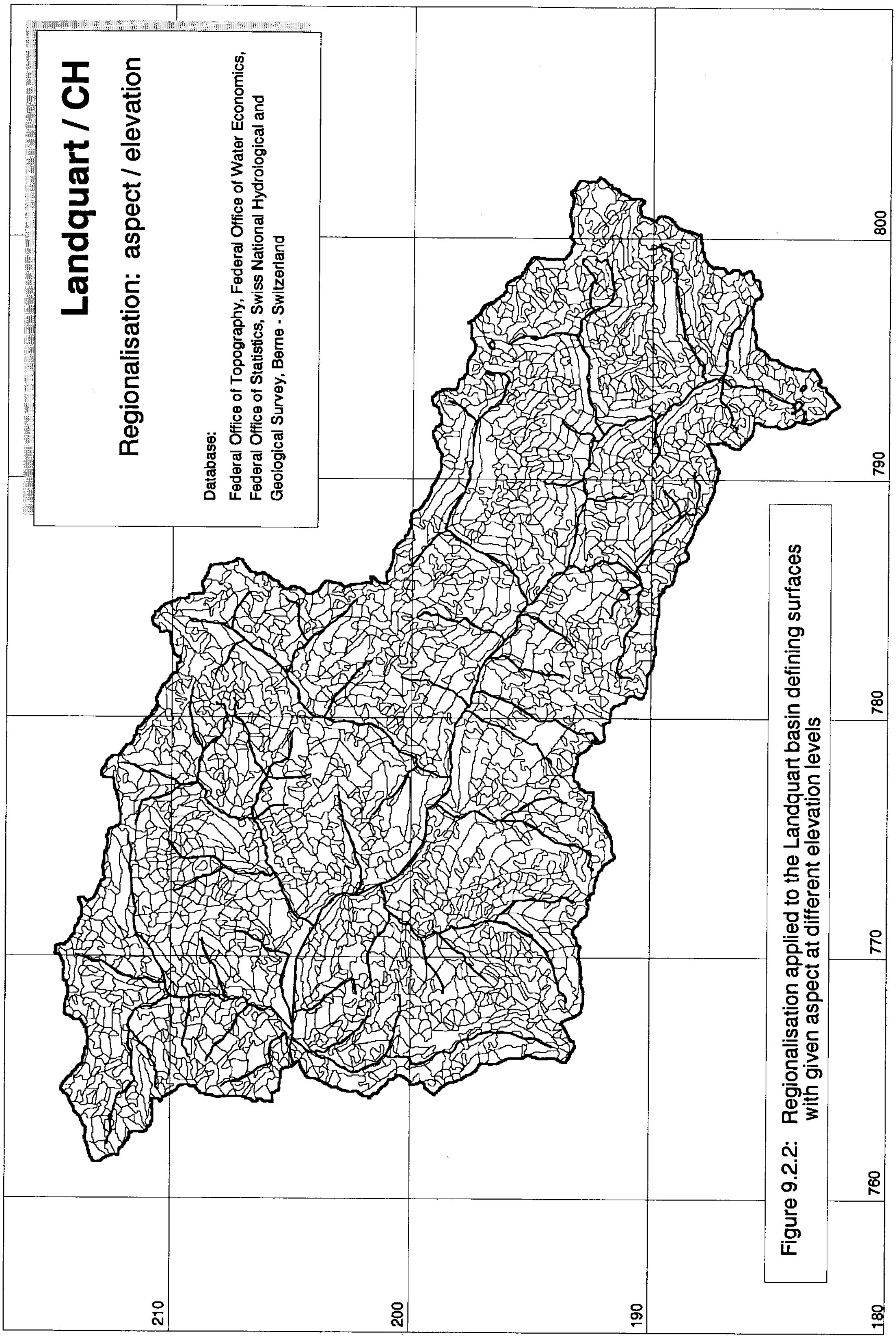
As this altitude slicing approach for the snow accumulation and melting procedure was not yet applied on the Ergolz and Murg catchments, this development has been adopted for the three chosen catchments. As the Ergolz and the Murg catchments are less steep and more compact, the precipitation has still been considered uniform on the catchments, though the temperature gradient was taken into account. Five altitude slices were used for the Ergolz catchment, against only four for the Murg catchment. These changes introduce small differences in the performance of the IRMB model in fitting the discharges observed when comparing the present report with the 1992 study (Schädler et al., 1992). In the sensitivity study of the climate change impacts on skiing activities, this not only allows consideration of the highest altitude range of the Broye catchment, i.e. from 1200 m to 1500 m, but also the 900 m to 1200 m range in the three catchments.

9.2.2 Development of an additional module to IRMB model for mountainous regions - the Landquart basin

(co-authors: E. Roulin, IRMB and
H. Aschwanden, LHG)

Introduction

Evapotranspiration and snow melt are two major processes governing the hydrological cycle. Both are driven by the energy available, mainly provided by the radiative net heat flux. The radiative regime in a mountainous environment depends upon exposure and shading effects. In order to simulate these major processes in the Landquart basin, the topography has been taken into account.



Database:
Federal Office of Topography, Federal Office of Water Economics, Federal Office of Statistics, Swiss National Hydrological and Geological Survey, Berne - Switzerland

Figure 9.2.2: Regionalisation applied to the Landquart basin defining surfaces with given aspect at different elevation levels

Figure 9.2.2

In order to be applied to alpine catchments, the IRMB model thus needs to be supplemented by a module able to reproduce the physical effects of the radiative regimes on evapotranspiration and snow melt.

A method has been developed in order to assess hourly values of the different shortwave and longwave components of the radiative net heat flux on sloping surfaces in a mountainous environment. This method was optimised in order to be applied to long time series. For this purpose, the Swiss National Hydrological and Geological Survey (LHG) has provided a dataset describing the basin on an irregular grid. Regionalisation has taken place using the ArcInfo GIS and the high resolution DTM of Switzerland to determine homogeneous surfaces in terms of slope, orientation and altitude. These homogeneous surfaces will constitute a partition of the catchment area in land units. Figure 9.2.2 gives the results of the regionalisation applied to the Landquart basin defining up to 2704 surfaces. A compromise between a complete description of the radiative fluxes and the computing efficiency is found by estimating these fluxes at the centroid of each unit and by supposing that the fluxes are homogeneous over the units.

Meteorological data provided by the SMI (Swiss Meteorological Institute) has been incorporated into a database in order to be efficiently handled during the simulations. Additional input data includes an adapted vegetation classification to describe the land use of the basin.

Using the results of the radiative net heat flux over the basin, processes occurring near the surface such as snow accumulation and melting, interception by the vegetation, soil drying and wetting and evapotranspiration are simulated for each cover type constituting each unit. After a distributed description of the surface processes, the various components of the water cycle are integrated and transferred to the combined modules of the IRMB model.

Outline of the method developed in order to assess the radiative budget

For a given place, direct solar radiation occurs when the sun rises above the skyline drawn by the surrounding mountains and by the slope itself (Figure 9.2.3). For each surface, the horizon is calculated at a 10° resolution in azimuth. The direct solar radiation is calculated by estimating its extinction through the atmosphere

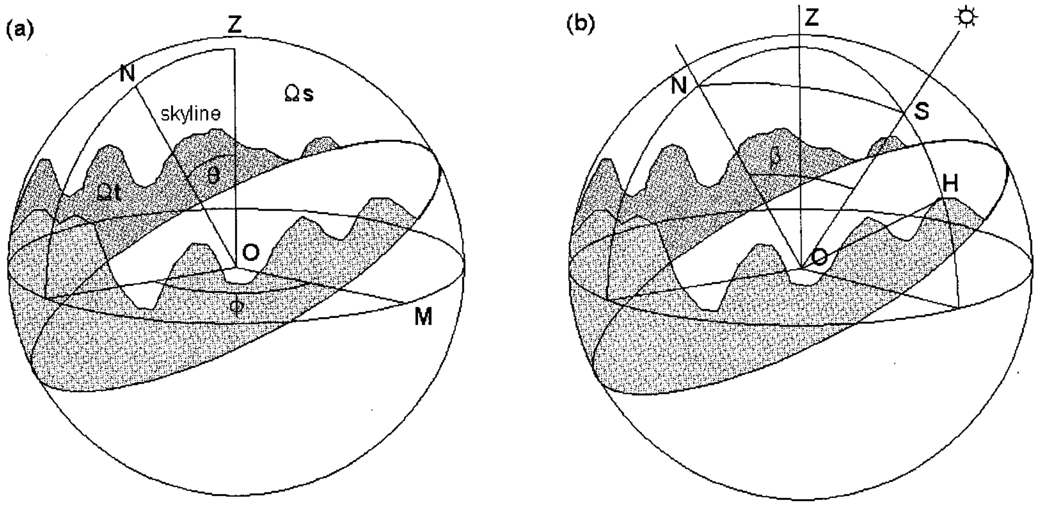


Figure 9.2.3 (a) Surface with slope θ and azimuth ϕ and the skyline projected on a sphere of unit radius. The shaded area is equal to Ωt, the solid angle sustained by the surrounding terrains whereas the area above the skyline is equal to Ωs, the solid angle sustained by the sky. O is the centroid of the surface, Z is the zenith, N is the normal to the surface and M is the origin for azimuth. (β) Direct solar radiation on an inclined surface; β is the angle of incidence of the sun's rays on the surface; S is the sun's direction, above the skyline at H.

taking into account both the optical depth as well as a turbidity factor depending on the air water content. The result is then weighed in terms of the sunshine duration. For these two steps, meteorological observations are interpolated at the centroid of each unit of the basin. Finally, the direct solar radiation is also affected by the angle of incidence of the rays onto the surface (angle β in figure 9.2.3).

The diffuse radiation in both the long waves and in short waves either from the sky or from the surrounding terrains is calculated by integrating radiances over solid angles (Ωs and Ωt given in figure 9.2.3). The radiances are calculated with an empirical formula using interpolated meteorological data as well as radiative properties of the land cover. Integrations are performed efficiently by the use of look-up tables giving shape factors for each unit.

The diffuse solar radiation is estimated on the basis of the radiance of the visible part of the sky. In a clear sky, radiance in a given direction in the sky depends upon the angle between the direction of the sun and the direction in the sky. Radiance is supposed to be homogeneous in sky sectors of 10° × 10° in zenithal and azimuthal angle. For each sector situated above the skyline, a shape factor is calculated taking the slope and aspect of the surface into account, and is stored in a look-up table. In the case of a cloudy sky, radiance is supposed to be homogeneous in strips of 10° in zenithal angle width. Shape factors for the strips of each surface are also calculated. The topography related effects are not negligible and in the case of some units, the visible part of the sky is lowered to a solid angle of 30% of the hemisphere centred on their normal. It would correspond to 77% of the shape factor of an hemisphere.

The radiance reflected by the surrounding surfaces is estimated on the assumption that reflection is isotropic, the shape factors calculated take the relative geometry between each couple of surfaces into account. The angle sustained by the surrounding terrains (Ωt, Figure 9.2.3) may comprise surfaces situated outside the basin as well as many units with a low contribution. The shape factor of the whole terrain seen from a given place is calculated. The shape factors of most contributing units are normalised against this terrain shape factor.

The infrared atmospheric radiation is calculated with a bulk formula using the interpolated screen air temperature, water vapour pressure and sunshine duration. Anisotropy of the radiance against the zenith angle is taken into account. The same shape factors of strips of 10° width as for the overcast sky are used to integrate the radiance over the solid angle sustained by the sky.

The terrestrial radiation emitted from surrounding surfaces that reaches the centre of a given surface is calculated using the same look-up table as for the reflected radiation. The infrared radiation emitted by a surface is estimated using an empirical ratio between 'equivalent surface temperature', and interpolated screen air temperature and estimated net visible radiation. The corresponding radiance is assumed to be isotropic.

Preliminary hydrological results

Simulations have been performed for periods of a few years using the first version of the regionalisation of the Landquart basin and with simplified information about the land cover. Precipitation is interpolated for each unit, taking into account the mean orographic gradient established with the monthly data of all rain gauges available in the basin and surroundings.

Two figures are presented here as examples of results. At the end of May, snow has melted in the main valley (figure 9.2.4) whereas mountains are still covered with a snow depth which depends upon the elevation but also on the aspect and geometric configuration of the surroundings. In the late summer, snow remains in some patches at the east of the basin, corresponding to glaciers situated upstream the Verstancla tributary.

An example of the daily potential evapotranspiration over the Landquart basin is shown in figure 9.2.5. As the radiative net heat flux provides most of the energy for evapotranspiration, the exposure and aspect of the surfaces explain much of the spatial variation.

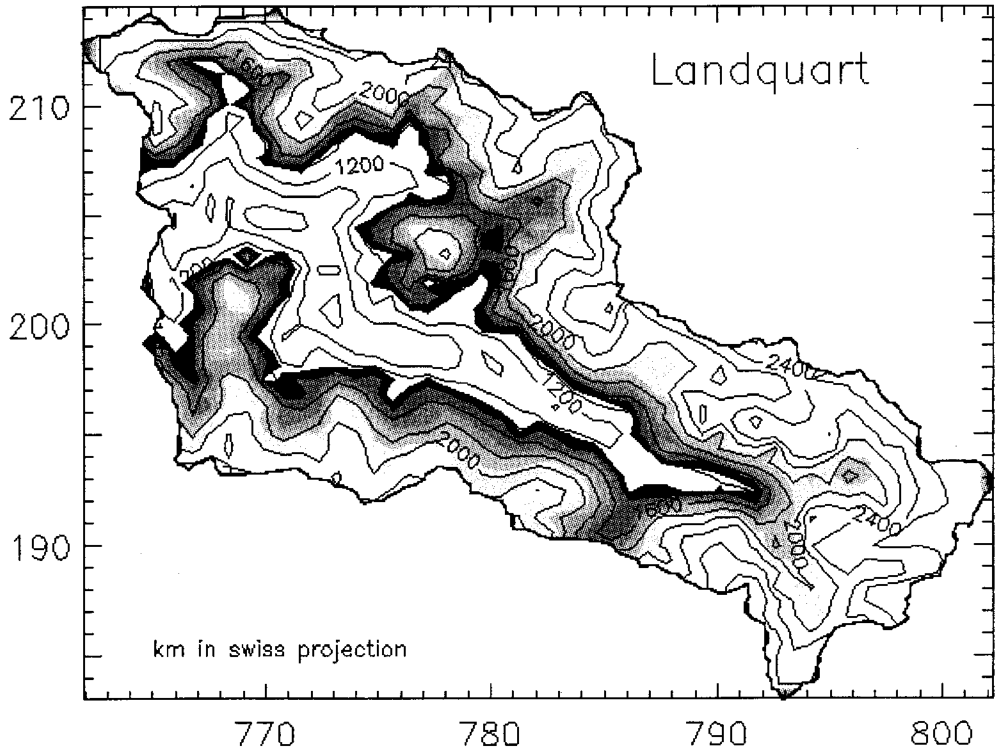


Figure 9.2.4 Water equivalent of the snow cover over the Landquart basin (Switzerland) at the end of April 1988, from 0 (black) to 1000 mm (white)

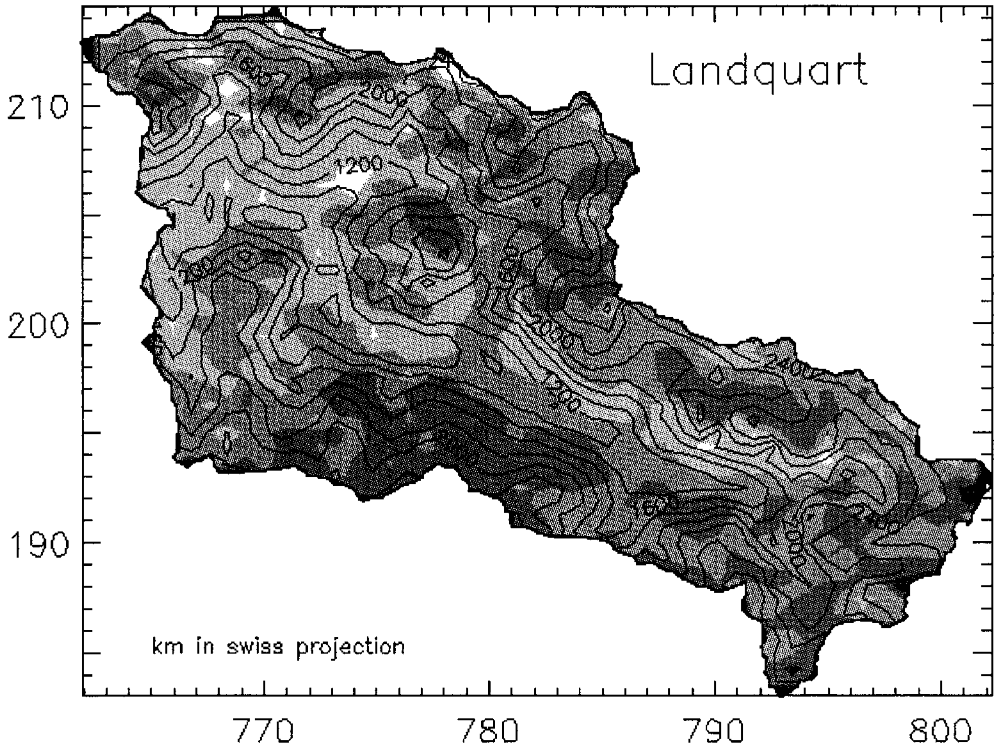


Figure 9.2.5 Daily potential evapotranspiration in the Landquart basin (Switzerland), 20th July, 1992, from 0 (black) to 15 mm/day (white)

9.3 Model development for the Thur catchment

9.3.1 General

In order to assess climate change impacts on hydrological processes, models are needed which are able to account for changing climatic conditions. In particular the consideration of land use, soil properties, and topography is important for a realistic estimation of both moisture extraction by evapotranspiration and runoff generation. This is assumed to hold true even under changed climate conditions. The model is expected to give results that allow for an estimation of changes in the water balance components and in flood and low flow frequency distributions. Therefore, the model should work in high temporal and spatial resolutions. To meet all these requirements, a new combined physically based/conceptual hydrological model was developed working in a horizontal resolution as the basis of a regular grid.

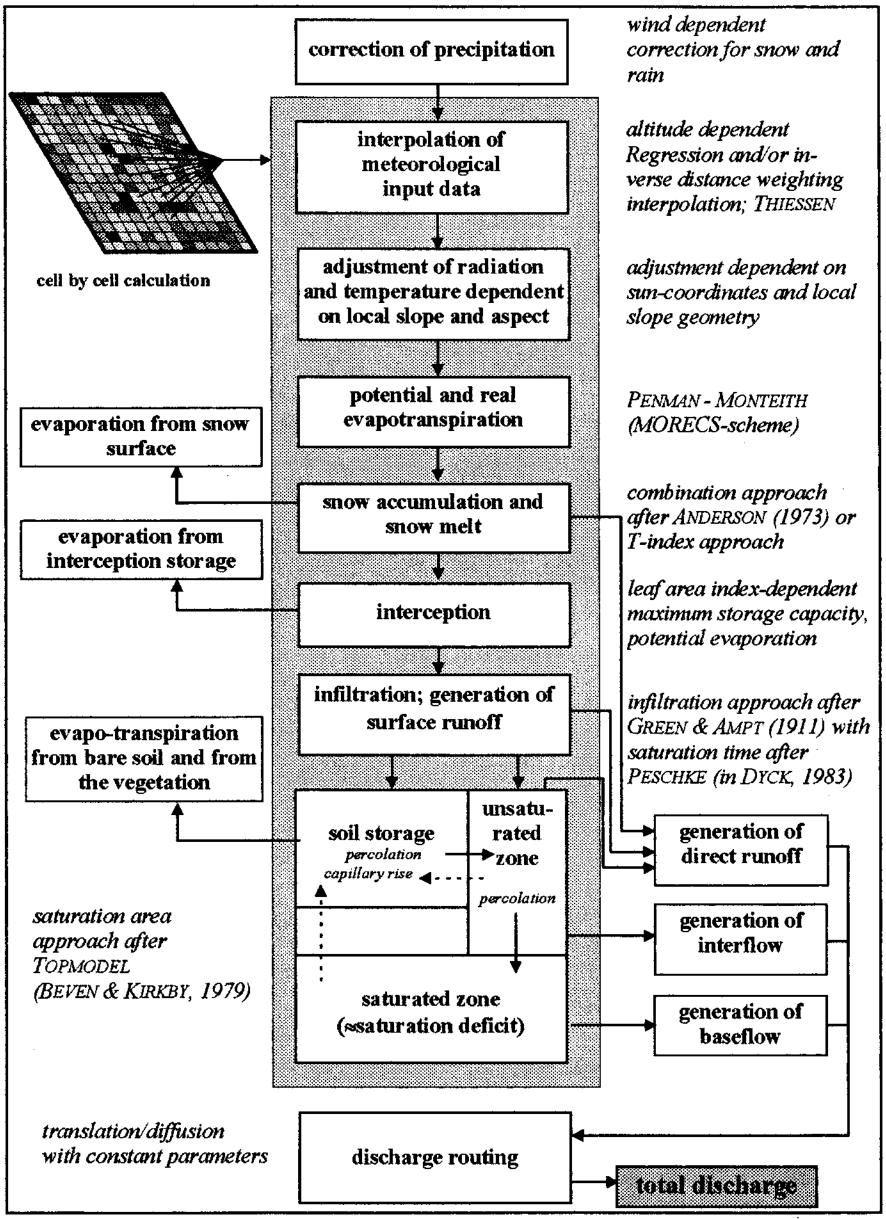


Figure 9.3.1 Structure of the Water Balance Simulation Model (WaSiM) of the ETH

The model structure of this 'Water Balance Simulation Model' (WaSiM) is outlined in figure 9.3.1. At the same time and parallel to this model development, a representative unit area model concept was employed to gain experience with various model types ('HBVEVATH' model).

9.3.2 The grid based model

The first type of model works on a cell by cell basis of a regular grid. The grid cell size i.e. the basic spatial resolution, may vary between a few metres and a few kilometres. The temporal resolution can be between one minute and one day. The temporal and spatial resolutions are usually relative to the size of the model area and to the hydrological problem dealt with (like floods, groundwater recharge or reservoir management). In mesoscale basins, resolutions of 0.5 to 1 km in space and 1 hour to 1 day in time have proved to be appropriate. The model is subdivided into several modules, which are described in the following paragraphs.

Prior to the data interpolation, a linear precipitation correction can be applied to the precipitation data, dependent on wind speed and distinguishing between air temperatures above and below the snow fall threshold. The interpolation of meteorological data needs specific attention in mountainous regions. In particular, the relation between altitude and various climatic variables has to be considered such as for air temperature, vapour pressure, wind speed, global radiation and for precipitation. Considering the possibility of one or two atmospheric inversions and a possible systematic horizontal shift, the altitudinal relation is expressed by a multilinear regression. Because of the great spatial and temporal variability of altitudinal gradients, for instance for precipitation and sunshine duration, the inverse distance weighting interpolation is also suitable as an interpolation technique. Interpolated values are calculated by considering the distance of interpolation location to measurement station locations only. Both interpolation techniques can be combined to get more realistic results by considering correlations of data with all three co-ordinates.

The model calculates adjustments for direct solar radiation for each time scale and for each grid cell, depending on aspect and slope of the grid cells and considering the shade provided by the surrounding mountains. Thus, the influence of topography on radiation and temperature driven processes, like evapotranspiration and snow melt, is considered. Radiation for shaded grid cells is corrected by reducing the interpolated radiation down to the level for diffuse radiation (given by a parameter). Additionally, the radiation adjustment is weighted by the relative sunshine duration, resulting in an effective adjustment of zero if the sun is not shining. The temperature adjustment uses similar ratios, depending on relative sunshine duration and on the radiation adjustment.

Following the data interpolation and the various data adjustments, the model calculates the water balance for each grid cell. Firstly, the potential and the real evapotranspiration is calculated. An approach according to PENMAN-MONTEITH (with minimal bulk-stomatal resistances) is used. The real evapotranspiration can be obtained by reducing the potential evapotranspiration depending on soil moisture contents or by increasing the bulk stomatal resistances depending on soil moisture, and calculating evapotranspiration values by means of these resistances. The evapotranspiration from snow covered grid cells is reduced due to reflection of global radiation (higher albedo values).

In the case of snow accumulation, a linear temperature transition zone approach is used. Thus, in a specified temperature interval, precipitation falls as a mixture of snow and rain with equal values in the middle of the temperature interval, 100% snow at the lower limit and 100% rain at the upper limit. The snow melt algorithms are based on the simplified energy balance approach of Anderson (1973). Such an approach also considers refreezing of liquid water stored in the snow cover at falling temperatures. If there is no precipitation in a time interval, snow melt is calculated using a simple temperature index approach, which can also be used as an alternative for the Anderson approach or for time intervals of less than one day.

The interception storage considers the storage effects of leaves and of the soil surface. The maximum storage capacity depends on the leaf area index. Depletion of this storage is possible by potential evapotranspiration. If the interception storage is completely filled, remaining precipitation is directly routed to the next model component, the infiltration model.

The infiltration model according to Peschke (in Dyck, 1983) uses an extended infiltration description based on the equations of Green and Ampt (1911). It generates a component of surface runoff, the infiltration excess. The infiltration algorithms distinguish between the unsaturated and the saturated phase.

The core of the runoff generation components is the soil model. This model component is responsible for water storage and for water flows in the root zone, in the unsaturated zone, and in the saturated zone of the soil. A variable contributing area approach based on the TOPMODEL algorithms is used (Beven and Kirkby, 1979; Beven et al., 1994). The fundamental principle of this model is the assumption that runoff generation is only affected by (a) the topography, described by the distribution of the topographic index and (b) a negative exponential law of decreasing hydraulic conductivity with increasing water table depth to the surface.

The WaSiM-ETH model contains three substantial modifications when compared with the original version of the TOPMODEL:

1. The calculation is carried out in a distributed way rather than in terms of classes of the topographic index, which would imply the hydrological similarity of all grid cells belonging to the same index class.
2. The common understanding of the TOPMODEL idea says, that there is only surface runoff and subsurface runoff, which is the runoff from the saturated zone and thus 'groundwater'. However, this 'subsurface runoff' should be referred to as interflow (Franchini et al., 1996). This is because of the low depth of the water table in the model, usually 0 … 0.5 m. A fast subsurface flow component, the fast interflow, was therefore additionally introduced. The interflow storage is a linear storage. By calibrating its time constant, it is possible to fit observed hydrographs in many catchments, much more effectively than without this runoff component. This is particularly true for catchments with stratified soils (gley, paragley).
3. The third extension to the original TOPMODEL version is the introduction of the possibility of refilling the evapotranspiration losses in the root zone by water uptake from the saturated zone and from the interflow storage. As observed hydrographs show, the saturated zone water level and therefore the baseflow may decrease much faster under certain conditions, due to evapotranspiration than only due to storage outflow.

The modified variable contributing area approach is a conceptual but efficient approach for generating surface runoff, (fast) interflow and subsurface flow (baseflow). The distribution of the topographic index and therefore the generation of the three runoff components depends on the topography of a whole catchment.

The entire basin can be subdivided into a number of subcatchments. The superposed runoff components of these subcatchments are then routed to the outlet of the entire basin. The routing method is a simple translation/diffusion model with a constant translation time and diffusion by a linear reservoir with a constant characteristic storage time for each channel.

Four efficiency criteria were employed for the quality of the model results: the explained variance coefficient (EV) and the coefficient of determination (r^2), for both linear and logarithmic results (see also Franchini et al., 1996). In the case of logarithmic EV and r^2, the simulated and observed discharges Q_{sim} and Q_{obs} were converted into their logarithms prior to calculation of the criteria. The 'linear' criteria EVl_{in} and r^2_{lin} are indicators of how effectively the model reflects the peak flows or flood response, whereas the 'logarithmic' criteria EV_{ln} and r^2_{ln} consider the entire discharge spectrum with the same weights and thus are indicators of how effectively the model fits the recession periods and droughts. Differences between explained variances (EV) and coefficients of determination (r^2) are indicators for a systematic shift of the simulated hydrograph with respect to the observed hydrograph. In an ideal case, all four criteria will be equal to 1.0; in practice, the EV value is often slightly larger than the r^2 value.

9.3.3 The representative hydrological unit area model HBVEVATH

This model is based on the HBV model (Bergström, 1976). In its new PREVATH (Precipitation Runoff EVAporation THur) version it has also been used for physically based estimation of impacts of climate changes on the water balance in the Thur basin. The most important extensions of the new model are as follows:

- *Spatially distributed modelling by using hydrologically similar units.* These units are distinguished by characteristic properties such as mean altitude, aspect, land use and soil properties. They can be derived by aggregating corresponding grid elements to hydrotopes. The complete HBV model scheme is applied to each of these hydrotopes. The knowledge of the exact location of single cells is not necessary for computation purposes.
- *Physically based estimation of evapotranspiration* using an approach very similar to an equation (9.3.8) based on the Penman-Monteith equation.

Although not a completely physically based model, these extensions are the basis for applications of the model for climate change impact studies. The runoff generation is equivalent to the HBV model. The input data is the data interpolated by WaSiM-ETH, while flow routing is also carried out in the same way as in WaSiM-ETH.

9.4 Development and description of the Saar model

To examine the impacts of climate changes on hydrological systems, the model must take into account all effects with respect to the study area. For the middle hill regions of Germany, the Hydrological Simulation Program Fortran (HSPF) was used. HSPF was developed for the U.S. Environmental Protection Agency and is available as a PC version (release 10). A detailed description is given in Bicknell *et al*, 1993. The model has been applied in a wide range of applications and catchments sized 50 km^2 to more than 7000 km^2 (Donigian et al, 1995).

HSPF can be characterised as a semi-distributed conceptual model. It calculates runoff and water balance in time steps ranging from 5 minutes to 1 month. A daily time step was chosen for this study. Within the bandwidth of the model error and the uncertainty of the scenarios, an analysis of daily discharges is appropriate in order to estimate the effects due to possible climate changes.

A schematic view of the model structure and representation of the hydrological cycle is given in Figure 9.4.1.

As outlined in paragraph 8.3, snow conditions have to be considered. In HSPF an energy balance snow model calculates the snow accumulation and melt processes. The algorithms used are based on the work by the Corps of Engineers (1956), Anderson and Crawford (1964) and Anderson (1968).

Interception is modelled as a simple storage that releases all excessive capacity water to the surface. The storage capacity may vary on a monthly basis for each land use.

Water from impervious areas is directly routed to the stream channel. Infiltration in pervious area is modelled on the basis of Philip (1959). A linear distribution function is used to take into account spatial variation within a hydrological unit.

Directly infiltrating moisture enters the rooted (lower) zone, water exceeding infiltration capacity is separated into overland flow, interflow and surface retention. Moisture entering the rooted zone can remain or further percolate to active or deep (inactive) groundwater. Water percolating to deep groundwater is lost from the system whereas active groundwater storage can become baseflow using linear reservoir routing with a non-linear option.

HSPF assumes potential evaporation to be an input time series. Calculation of potential evaporation for each land use is done via an evaporation model developed at BfG (Liebscher et al, 1995) based on the well-known Penman-Monteith equation. Actual evaporation is calculated as being snow evaporation, interception, evaporation from upper and lower soil zone as well as from active groundwater.

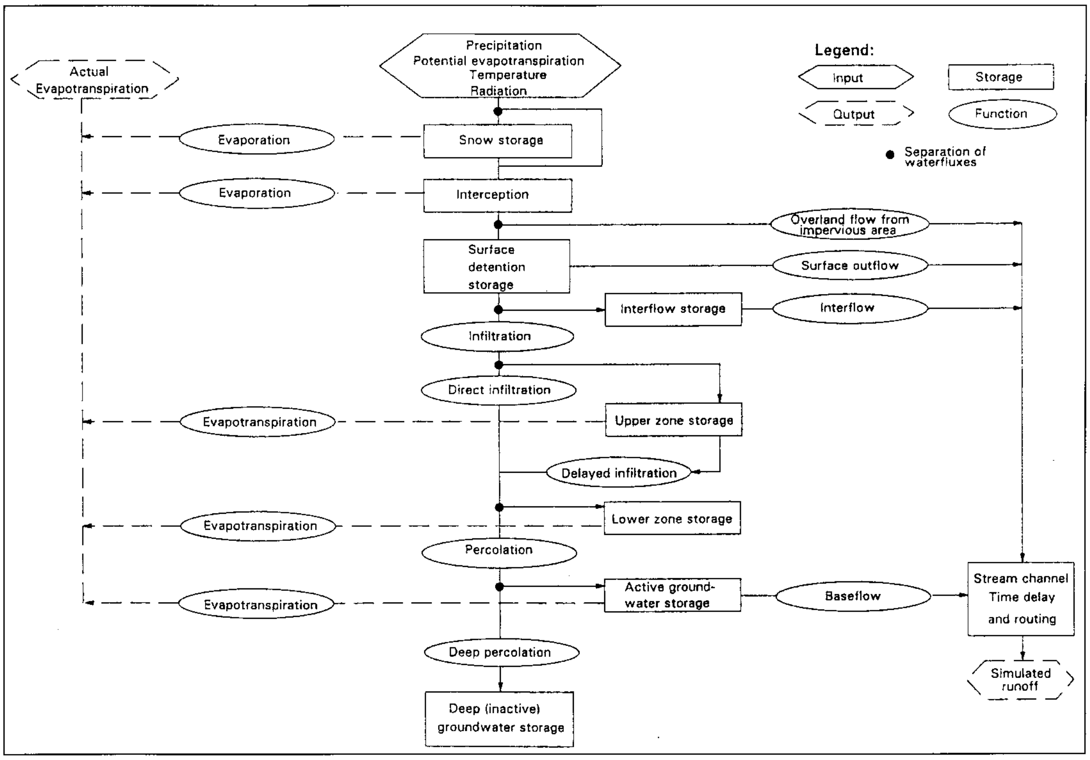


Figure 9.4.1 Schematic view of HSPF model structure

Flood routing is done using the modified pulse method, a variation of the storage routing method, whose accuracy is appropriate for the purpose of this investigation.

Spatial variation in catchment characteristics within each subbasin are taken into account by linking all areas with similar hydrological properties to a hydrological response unit. Model output is calculated for each of these units.

9.5 Development and description of the lowland model for the Vecht

The lowland model describes processes that are directly influenced by climate and land use changes, such as evapotranspiration, in a physically based way. Processes that are not directly influenced by climate parameters, e.g. transport of water to the drainage system, are described in a more conceptual manner. Processes that are of minor importance in the lowland part of the Rhine basin, like snow melt, are not incorporated in the model. To account for spatially varying parameters, such as land use and soil-physical characteristics, a distributed model with a spatial base of 250 × 250 m was used. The temporal resolution was set at one day. This is a minimum requirement for the analysis of frequencies of discharge peaks. For modelling purposes, the Vecht catchment was divided into subcatchments that are connected by deep groundwater flow, and the main water courses of the catchment (figure 9.5.1). Accordingly, the model was divided into a hydrological and a flow-routing component. The general model structure is shown in figure 9.5.2.

9.5.1 Hydrological component

The hydrological component of the lowland model computes actual daily evapotranspiration and, subsequently, discharge for each subcatchment. Spatial variation within a subcatchment is considered by distinguishing areas with different combinations of land use, soil-physical properties, and seepage. This data is combined in a geographical information system (GIS) (figure 9.5.3). Areas with equal characteristics of land use, soil-physical properties and seepage are combined in one hydrological unit. A unit is schematised as a column with four lay-

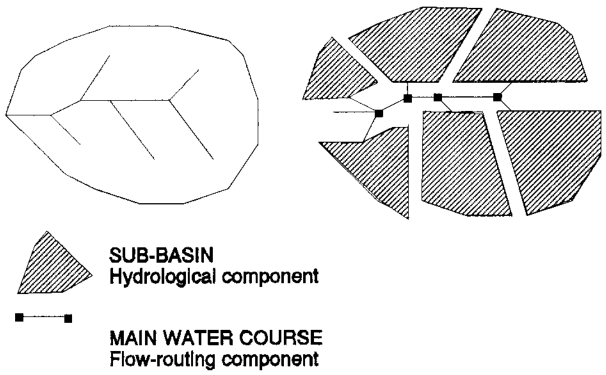


Figure 9.5.1 Schematic representation of a drainage basin, with a hydrologic component and a flow-routing component

ers, representing the *atmosphere*, the *vegetation*, the *unsaturated zone* and the *saturated zone* respectively. Characteristic for the lowland area is the shallow depth of the phreatic water table and its important role in hydrological processes. A special type of hydrological unit is the paved part of a subcatchment, that is connected to a sewer system. A separate model was developed for this unit.

Evapotranspiration and groundwater flow

Flow processes in the vegetation and in the unsaturated zone layers are described by the MUST one-dimensional model (Model for the Unsaturated flow above Shallow water; De Laat, 1980, 1985, 1989, 1992). This model describes vertical transport of soil moisture using equations of Darcy and continuity, and computes actual evapotranspiration. The unsaturated zone is subdivided in a root zone and the subsoil (see figure 9.5.4). Flow in the root zone (q_s) is governed by water uptake by roots.

The computation of actual and potential evapotranspiration is based on the Penman-Monteith equation for those land use types for which the required crop parameters are available (Monteith, 1965). Otherwise, potential evapotranspiration is computed with the Penman open water crop factor method, and a sink term is used to calculate actual evapotranspiration. For the sealed ('paved') part of a subcatchment, actual evapotranspiration is assumed to be equal to the Penman open water evapotranspiration as long as the surface is wet. Evapotranspiration at dry surfaces is zero.

The lower boundary of the MUST model is defined by the groundwater flux to open water (q_1), combined with a seepage flux from/to deeper layers (q_2). According to the model concept to describe the groundwater reservoir, the q_1-flux increases exponentially with a rising groundwater table (Belmans et al., 1981). The q_2-flux is computed by a steady-state groundwater model, NAGROM, that describes flow through the *saturated zone* (De Lange, 1991). In this model, different parts of the geo-hydrological system, such as polders and infiltration areas, are described as separate elements. A constant seepage (or infiltration) flux is computed for each element.

The required input data for MUST is meteorological data, which determines the upper boundary condition. Where the Penman-Montheith method is used, this comprises precipitation, temperature, relative humidity, wind speed, and sunshine duration. If the sink term is used, precipitation and potential evapotranspiration determine the upper boundary. Furthermore, data is needed on soil water retention, hydraulic conductivity relations and crop characteristics, including rooting depth, crop height, soil cover, and albedo.

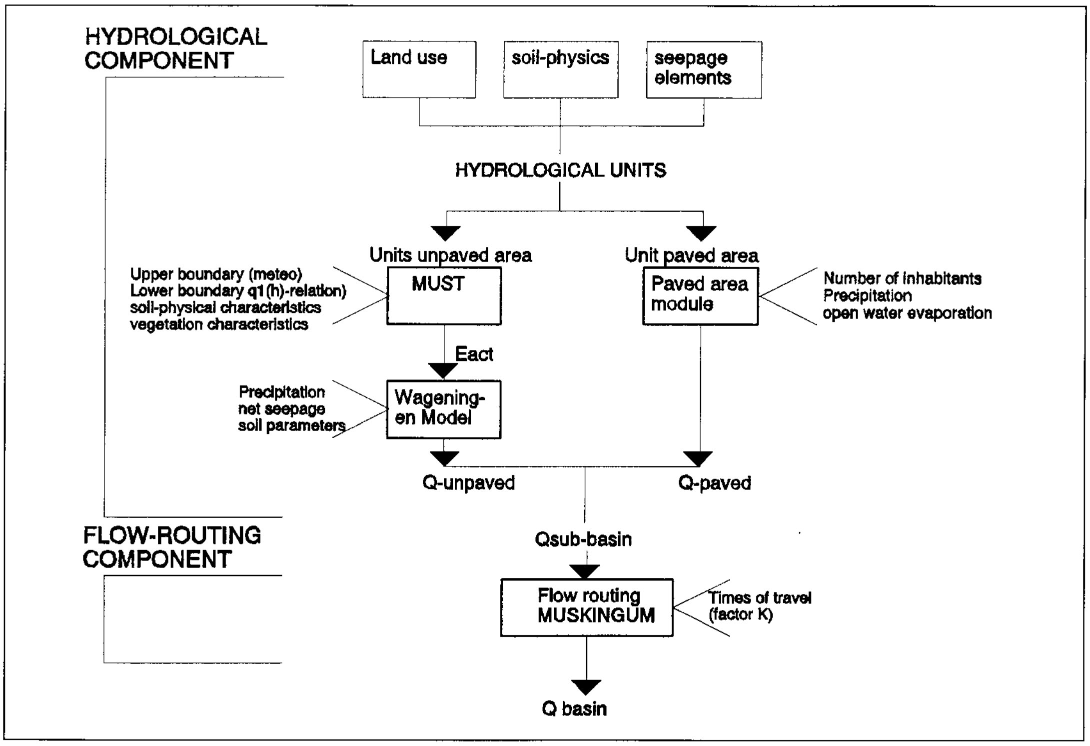


Figure 9.5.2 The structure of the lowland model

Discharge of a subcatchment is modelled in a more conceptual manner. For the unsealed area (> 95% of the total area), a conceptual rainfall-runoff model, the Wageningen Model, was used (Warmerdam, 1993). The flow chart for the model is given in figure 9.5.5. The model requires areal average precipitation (P) and actual evapotranspiration (E) as input. Evaporation is calculated using the MUST model. In addition, soil moisture content at field capacity (FC), and soil moisture content at saturation (SAT) are required for each subcatchment. Finally, to account for groundwater flow from one subcatchment to another, a net seepage term (SP), representing the flux across the watershed, was added to the model as input to the groundwater reservoir.

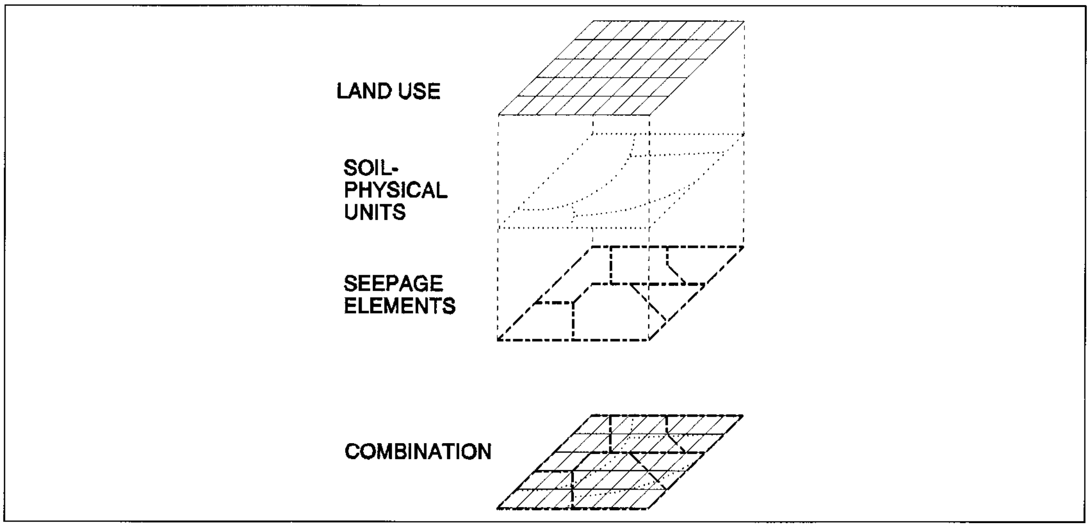


Figure 9.5.3 Combination of land use, soil-physical and seepage data in a geographic information system

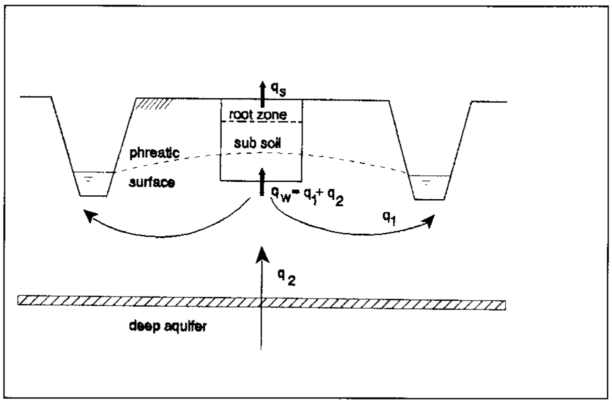


Figure 9.5.4 Schematisation of unsaturated zone as applied in MUST

Effective precipitation is divided over a fast and a slow component. The contribution of the fast flow component is assumed to increase linearly with rising groundwater table. The fast component is described by a convection-diffusion model for non-steady channel flow. For the slow component a non-steady groundwater model describing groundwater flow between two lateral channels, the so-called J-model, is used (Kraaijenhoff van de Leur, 1958). The model uses six parameters in total, which have been optimised with time series of observed discharge.

Discharge from sealed areas is modelled using a simple reservoir model of the sewer system. The model consists of two reservoirs, one accounting for surface storage of precipitation, and the other one simulating the sewer system that discharges the effective precipitation of the sealed areas, and domestic and industrial waste water.

9.5.2 Flow-routing component

The flow-routing component of the lowland model combines the subcatchments and routes their discharge to the outflow point of the Overijsselsche Vecht catchment. The Muskingum method was chosen for this purpose (Chow et al., 1988).

9.6 Concept of the RHINEFLOW model

During the last decades many models have been developed that describe the transformation

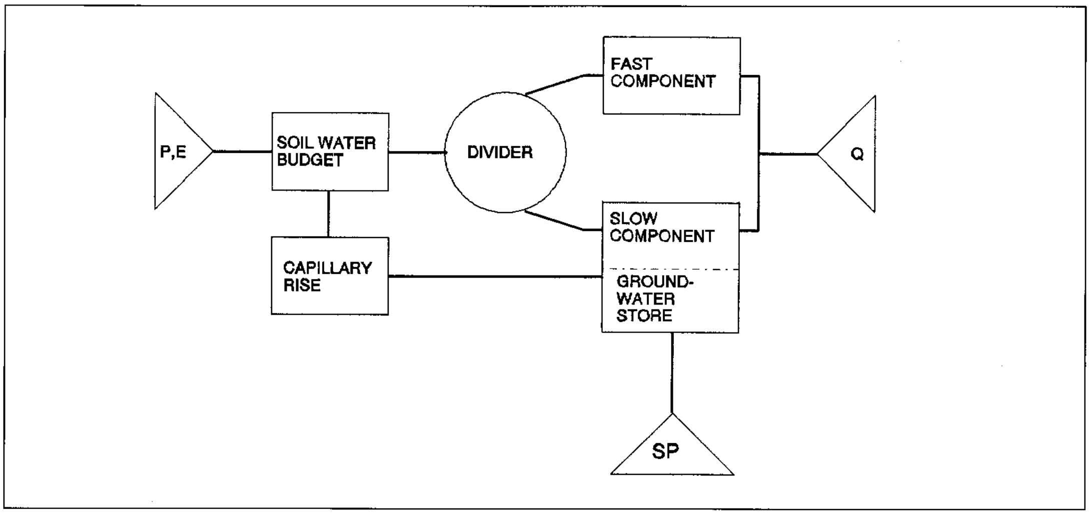


Figure 9.5.5 Flow chart of the Wageningen Model, as used in the lowland model to simulate the rainfall-runoff process of the unpaved part of a sub basin.

of precipitation into runoff (e.g. Franchini and Pacciani, 1991). However, existing models that can be applied to various basins such as the SACRAMENTO model, TOPMODEL (Beven et al. 1984), and the SHE model (Abbot et al., 1986), require large detailed data sets both in space and in time. Even in a densely measured area such as the River Rhine catchment, data for many of the parameters such as geo-hydrological properties, land management and vegetation types, and hydraulic channel properties is only available at a very low spatial resolution. One can use statistical methods to estimate these values from small scale units or laboratory studies, but the problems of up-scaling these parameters and variables to large scale phenomena are still unsolved (e.g. Beven, 1989). This implies that there is no accurate data to feed these models. Finally, due to their large spatial and temporal resolution the models are very time consuming in computing when used for a large catchment such as the Rhine. Consequently, these models are too complex for an approach to model the Rhine catchment on a monthly time basis using a limited data set and limited computing resources. As a result, the discussions between the members of the CHR led to the conclusion that there were no existing models that could be integrally used for modelling the Rhine (CHR, 1991).

The RHINEFLOW model is a water balance model for the River Rhine Basin developed at the Department of Physical Geography of the University of Utrecht, the Netherlands. It is designed to study the sensitivity of the discharge of the River Rhine to a climatic fluctuations. Model structure, data requirement and model performance are discussed in detail elsewhere (van Deursen and Kwadijk, 1993; Kwadijk 1993); Here we only give a brief overview.

The RHINEFLOW model calculates the transfer from precipitation to runoff in the Rhine Basin, using four storage forms. These represent the major water storage compartments: snow, soil, groundwater and lakes (CHR 1976). The model uses standard climate data, monthly temperature and monthly areal precipitation and geographical data on topography, land use, soil type and groundwater flow characteristics, to calculate this transfer. The model produces month to month runoff for the River Rhine and for its main tributaries. In addition it produces spatially distributed monthly evapotranspiration and temporal storage of water as snow.

All variables and parameters are stored in a Geographical Information System grid. For this study the spatial resolution was 3*3 km. The model has been implemented in this GIS using generic functions (Van Deursen and Kwadijk 1993). Monthly storages, flows and losses are calculated for each grid cell. The model output is in form of grid maps and time series. Figure 9.6.1 shows a flow diagram of the model.

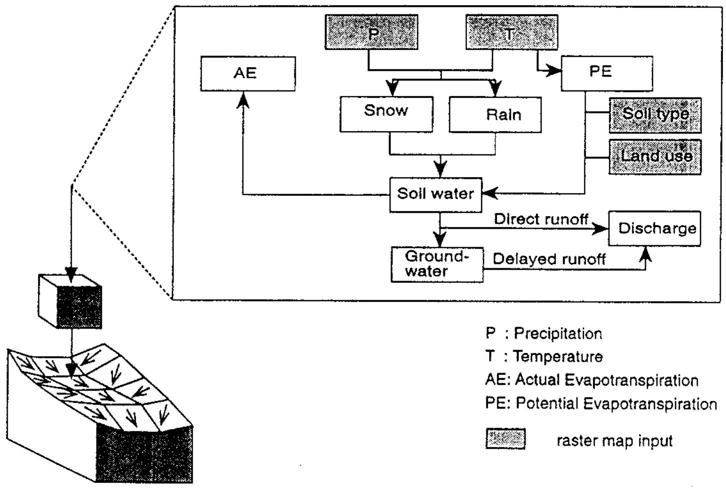


Figure 9.6.1 Flow diagram of the RHINEFLOW model

The RHINEFLOW model calculates monthly potential evapotranspiration using the temperature dependent Thornthwaite equation (Thornthwaite and Mather 1957). For actual evapotranspiration calculations the results were modified with a factor for different rates of evapotranspiration as a function of land use type. Using the equations of Thornthwaite and Mather (1957) the calculations for actual evapotranspiration also take possible soil water deficiencies into account . Temporal snow storage is calculated by assuming that precipitation falls in the form of snow when the average monthly temperature is below 0°C. Snow melt starts when the average monthly temperature is above 0°C and increases with temperatures above 0°C.

The monthly water surplus produced is proportionally separated into rapid runoff (20%), which is available for discharge in the month in question, and a volume of water which is added to the groundwater storage (80%). Based on the groundwater volume, the delayed runoff, representing the base flow of the river, is calculated with a linear recession equation. This recession equation is calibrated for the main tributaries, using the observed streamflow of low flow months. Since base flow characteristics mainly depend on geo-hydrological properties of a catchment, it is assumed that this equation will not alter under changing climatic conditions.

Basin streamflow is obtained from the grid cell water balances by adding water production (rapid and delayed flow) for all cells situated in a (sub)catchment. This assumes that all water available for runoff leaves the catchment within one time step. A monthly time step was found to be reasonable for the Rhine basin.

Month to month discharge is influenced by temporal storage and drainage of lakes in the area above Basel (Switzerland). Since almost all lakes are artificially regulated this term is not incorporated in the model. Streamflow calculations are corrected by using observed data for lake water storage changes.

10 Climate change scenarios

10.1 Introduction

Three Climate change scenarios have been provided by the Climate Research Unit, University of East Anglia with the assistance of the Institute of Hydrology, Wallingford (Project Progress Report 1996). The scenario sets assume a business-as-usual development with no measures to reduce the emission of greenhouse gases. The construction of the scenarios is based on climate change experiments using three General Circulation Models (GCM) and are described by Hulme et al. (1994). Two equilibrium experiments (UKHI, XCCC (equivalent to CCC)) and one transient experiment (UKTR) have been examined for different target periods. For the XCCC and UKHI scenarios the years 2020, 2050, and 2100 and for the UKTR experiment, the periods 2031-2040 and 2066-2075 have been examined. Though all scenarios were run, this study will focus on the results for the year 2050 which is within the planning horizon of decision-makers and represents a linear interpolation from present-day conditions to the year 2100. For each scenario, mean monthly changes in temperature, precipitation, wind speed, radiation, and vapour pressure have been provided on a grid of 0.5° × 0.5° longitude/latitude.

It should be noted, that there are some important limitations concerning the resulting scenarios. Scaling of standardised equilibrium GCM results by a magnitude of global warming factors assumes a constant spatial pattern of climate changes within time (Hulme et al., 1994). The validity of such an assumption is not clear a priori. Another limitation is the kind of interpolation of coarse-scale GCM output to a fine-scale resolution of the climate scenario (downscaling). For the application of the catchment models, the scenarios posed several problems in terms of temporal and spatial resolution and the assumption of the present-day validity of the statistical distribution e.g. of precipitation under climate change conditions, which is uncertain. Another shortcoming of the scenarios is the uncertainty in the development of evapotranspiration, which is the major driver of energy exchange between land surfaces and the atmosphere and therefore of the behaviour of the hydrological cycle. Under other climatological conditions, evapotranspiration may change into a feedback process between increased CO_2 concentration and stomata reaction of plants as well as a function of future land use patterns. For the purpose of the study, the development of evapotranspiration has been largely viewed as a function of air temperature. The use of the scenarios therefore has been guided by pragmatism on the basis of current knowledge.

10.2 Climate change scenarios for the Rhine basin

An estimation of the effects of climate changes on the Rhine basin requires the following procedures:

1. (a) Define a baseline climate and (b) the corresponding hydrological regime (the so-called control run).
2. Define one or more climate scenarios as a change in temperature and precipitation.
3. Implement the scenario climate on the baseline climate.
4. Calculate the hydrological regime corresponding with the climate scenario.

Baseline climatology (1a) and baseline hydrological regime (1b)

The month-to-month temperature from 27 weather stations in the Rhine basin was used as the baseline temperature for the 1960-1980 period (240 months). Precipitation was defined as the month-to-month areal precipitation of 14 subcatchments covering the entire basin over the same period. Using this baseline climate as model input, the Rhineflow model calculated the month-to-month water balance in the Rhine basin and the month-to-month discharge for a number of gauging stations that represent the discharge regimes of the Rhine river and its main tributaries.

Climate scenarios (2)

The climate scenarios were provided by the Climate Research Unit of the University of East Anglia. The methodology followed to construct these scenarios is comprehensively described by Hulme et al. (1994).

Global warming projections based on the equilibrium experiments using different Climate Models (GCMs) were calculated for the years 2020, 2050 and 2100. The transient response experiments provided projections for the 2031-2040 and 2066-2075 periods. In this way we arrive at eight different climate scenarios. In this report we focus on the results of the 2050 and the transient 2066-2075 projections.

The scenarios consist of changes in average monthly temperature (degrees Celsius) and precipitation (percentage) for these years on a grid of 0.5 to 0.5 degrees longitude/latitude. From the 0.5 to 0.5 long/lat grid we extracted the window that covered the Rhine basin. Each 0.5 by 0.5 degrees long./lat. grid cell was converted into the grid used by the RHINEFLOW model.

Projection of climate changes on the Rhine basin and calculation of future hydrological regimes (3,4)

For the RHINEFLOW model, the climate change scenarios derived from the CRU were projected on the Rhine basin with:

$$Ts(x,y,m) = To(x,y,m) + dTs(x,y,m) \text{ (degrees Celsius)} \tag{1}$$

where Ts(x,y,m) is the scenario temperature in cell (x,y) in month m; To(x,y,m) is the baseline temperature in cell (x,y) in month m; dTs(x,y,m) is the *average* temperature change in cell (x,y) in month m according to the GCM results used. (x,y) refers to the location of the grid cells of the geographical database used by the RHINEFLOW model.

Precipitation changes were defined as:

$$Ps(x,y,m) = Po(x,y,m) + dPs(x,y,m) * Po(x,y,m) / 100 \text{ (mm)} \tag{2}$$

where Ps(x,y,m) is the scenario precipitation in cell (x,y) in month m; Po(x,y,m) is the baseline precipitation in cell (x,y) in month m; dPs(x,y,m) is the *average* precipitation change (%) in cell (x,y) in month m according to the GCM results used.

This procedure yielded two time series, one time series for temperature and one for precipitation. Each time series covers a period of 240 months. The method used assumes that monthly variability of precipitation and temperature will not alter under scenario conditions. This assumption may have great effects on estimations of changes in frequency and magnitude of extreme low and high discharges. Although changes in mean runoff may be estimated with some reliability, the analysis of the changes in extreme events should be interpreted in a qualitative way.

Finally, the thus derived climatic time series for each climate scenario was used as model input for the RHINEFLOW model. This model calculated month-to-month discharges for selected gauging stations, annual water availability and snow cover duration.

10.3 Murg, Ergolz and Broye catchments

For each catchment, the closest grid point to the outlet has been chosen for extracting the scenarios from the database. The three catchments have been submitted according to scenar-

Table 10.3.1 Precipitation scenarios. Relative increments (%) corresponding with the stationary UKHI and CCC experiments for the Broye, Ergolz and Murg catchments in 2100

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	year
UKHI2100													
Broye	27.66	19.42	13.83	9.04	0	–11.17	-15.69	–21.28	–27.13	6.38	6.38	20.75	1.5
Ergolz	31.39	22.61	16.49	12.24	0.27	–9.04	-14.10	–20.48	–26.33	9.58	4.79	23.41	1.9
Murg	30.86	24.74	16.76	10.91	0.27	6.92	-13.30	–18.62	23.94	8.25	5.32	23.94	2.5
XCCC2100													
Broye	28.20	16.49	22.61	14.36	0.27	–7.45	–20.22	–10.64	–13.03	–0.27	17.29	24.21	5.0
Ergolz	28.73	17.82	23.94	14.10	1.86	–6.38	–19.42	–10.11	–12.77	1.06	19.15	24.74	4.7
Murg	28.46	18.35	24.21	14.90	2.39	–6.12	–19.15	–10.37	–12.50	0.53	19.68	24.74	4.8

ios corresponding to the 18701370 point for the Broye catchment, 18751375 for the Ergolz catchment and 18901375 for the Murg catchment.

As their associated grid points are different, the scenarios corresponding with the three catchments are not exactly the same. Table 10.3.1 illustrates the differences between the monthly precipitation increments adopted for the UKHI2100 and XCCC2100 scenarios. Although these differences are small, they represent around one per cent on average. Combined with the yearly precipitation amount, the precipitation increment in the XCCC2100 scenario supplies some 70 additional millimetres to the Broye catchment and only 50 millimetres to the Ergolz catchment. The average scenarios described in table 10.3.2 give a condensed survey of the climate trends adopted for the present study.

Almost all the *precipitation* scenarios are characterised by an annual increase in precipitation amounts. For the stationary experiments, the proportionality between the time lags is clear. The 2050 increments are approximately twice as large as those of 2020, while the 2100 increments in turn are twice as large as those of 2050. Due to the non-stationary approach followed in the UKTR experiment, this is not valid for the corresponding increments. The most salient feature of the scenarios is the increase in precipitation during the winter season, from October through to May, with a maximum in the December-March period. Summer precipitation is reduced from June through to September. The XCCC experiment gives a stronger precipitation increase than the UKHI simulation. The UKTR2020 scenario is the only one to present an additional decrease in precipitation in March and April. In this particular scenario, this six-month precipitation reduction induces a slight

Table 10.3.2 Scenarios corresponding with the stationary UKHI and XCCC experiments and the transient UKTR experiment and the yearly mean of these increments

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	year
Precipitation: Relative monthly increments (in %)													
ukhi2050	15.55	11.54	8.14	5.57	0.09	–4.69	–7.45	–10.44	–13.39	4.19	2.85	11.77	1.0
xccc2050	14.77	9.11	12.24	7.50	0.78	–3.45	–10.17	–5.38	–6.62	0.23	9.71	12.74	2.5
uktr2050	10.20	15.83	24.07	1.67	1.67	–5.20	–2.27	33.57	–20.23	3.27	21.00	19.70	1.7
Temperature: absolute monthly increments (in °C)													
ukhi2050	2.81	3.04	2.48	1.98	1.75	1.66	1.61	2.48	2.53	2.12	1.38	2.07	2.16
xccc2050	1.24	1.38	1.10	0.83	0.97	1.10	1.38	1.24	1.43	1.24	1.24	1.15	1.19
uktr2050	2.97	1.77	3.93	0.73	1.73	1.53	2.50	3.70	4.67	2.20	2.87	4.33	2.74
Water vapour pressure absolute monthly increments (in tens of hPa)													
ukhi2050	10.07	11.92	10.26	10.58	11.96	10.30	6.35	5.75	5.47	10.30	8.00	10.12	9.26
xccc2050	6.71	8.37	6.85	6.35	9.06	13.61	17.94	13.16	14.54	10.54	9.20	6.81	10.26
uktr2050	0.80	0.70	1.50	0.10	1.30	0.97	1.90	0.73	0.93	1.30	1.50	1.53	1.11
Relative humidity of the Murg catchment: absolute monthly increments (in %)													
present	89	87	78	73	71	72	71	72	79	84	87	87	79
ukhi2050	–3	–2	–2	0	1	–2	–4	–7	–9	–3	2	1	–2
xccc2050	2	4	2	2	2	3	2	1	1	1	4	3	2
uktr2050	–17	–11	–18	–4	–7	–6	–9	–13	–20	–11	–15	–22	–13
Wind speed: relative monthly increments (in %)													
ukhi2050	7.73	7.04	5.94	1.75	–1.89	0.97	3.36	2.21	–2.30	1.15	0.41	3.82	2.51
xccc2050	2.30	1.84	3.91	5.24	1.65	–6.16	–5.98	–3.50	–6.71	–1.52	0.55	2.67	–0.48
uktr2050	2.37	13.87	8.53	2.07	–5.17	5.00	–2.43	–0.80	–3.50	8.67	12.50	6.90	4.00
Radiation budget: absolute monthly increments (in Wm^{-2})													
ukhi2050	11.10	11.97	10.77	11.00	13.57	13.00	10.50	10.77	9.77	13.77	9.37	11.97	11.46
xccc2050	8.43	9.03	6.90	6.17	9.07	12.50	23.43	17.30	18.73	12.87	10.73	9.43	12.05
uktr2050	1.43	0.07	–3.53	1.90	0.50	3.53	4.33	12.87	5.90	2.33	1.27	4.67	2.94

decrease in annual precipitation amounts for the three catchments.

The projected *temperatures* are all higher than in present-time conditions. The UKHI experiment gives the largest increase during winter and the smallest in June-July. The XCCC experiment does not give such a great contrast between the seasons and gives significantly lower temperatures than the UKHI experiment. For the year 2050 horizon, the transient experiment even gives slightly higher temperatures than the two stationary simulations, which is a little bit surprising given the method according to which this simulation is built. In addition, the transient increments seem to be more disturbed (greater month-to-month variability) than the two others.

The development of *water vapour pressure* is of great importance in estimating the potential evapotranspiration, PET, under GC climate conditions. The largest increase in water vapour was simulated by the XCCC experiment during summer. As direct reading of this data is not possible, relative humidity has been assessed on the basis of monthly temperature and vapour pressure. The result for the Murg catchment is given in table 10.3.2. Similar results are provided by the two other catchments. In the stationary experiments, relative humidity develops rather smoothly from one time lag to another. Relative humidity in UKHI scenarios is lower than the present values, while the reverse is simulated in the XCCC experiment. Although relative humidity can no longer be considered as remaining unmodified under GC conditions, the values obtained do not deviate very much from today's values. The transient scenarios give larger modifications in relative humidity. This must be kept in mind while interpreting the GC impacts on evapotranspiration.

The CRU scenario database also provides information on the development of *wind speed* and of *radiation budget*. These variables are used to assess the PET under GC conditions and to estimate snow cover melting. The UKHI experiment indicates increased wind speed almost throughout the year. Contrary to this, the XCCC experiment only shows a slight increase in wind speed from November through to May and a decrease during the rest of the year. Increments are more scattered in the case of the UKTR experiment. The radiation budget rises under GC conditions. Only one monthly increment in the UKTR2050 scenario is negative.

10.4 Thur catchment

All climate change scenarios were applied to the actual climate of 1981 to 1995 model time period. Whilst the method is very crude, it is the most simple way to apply mean monthly changes (interpolated in time to the actual day) linear to the actual climate variables. Figures 10.4.1 and 10.4.2 show the mean monthly changes in temperature and precipitation for selected scenarios for the Thur basin (mean of the four cells of the 0.5° grid covering the Thur basin). Figure 10.4.3 shows two examples for application of the UKTR6675 scenario (results from the UKTR experiment, mean changes over the last 10 years). A control run for the present period was also carried out in order to calculate the differences between scenario hydrological behaviour and present-day hydrological behaviour.

10.5 Saar catchment

The figures 10.5.1 to 10.5.4 show the mean monthly changes in temperature and precipitation for the catchments of the Prüm and Blies rivers according to the XCCC2050, UKHI2050, and UKTR6675 scenarios. In general the changes for both study areas look very similar.

The XCCC2050 scenario

Compared to the other scenarios, the results of the XCCC experiment are quite moderate. The annual increase in air temperature is 1.11°C for the Prüm and 1.13°C for the Blies. There are no major seasonal variations except for springtime where changes are below the other seasons. The precipitation scenario indicates a significant 10 to 15% increase during winter and a 5 to 10% decrease during summer. Between these extremes, a smooth transition takes place during spring and autumn, and the changes from month to month are almost continuous. A total increase in precipitation of about 4% is indicated for both study areas.

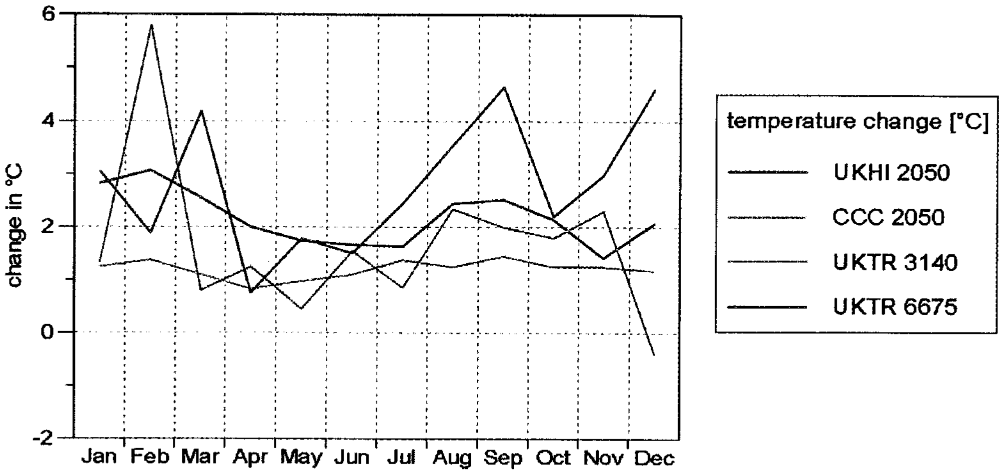


Figure 10.4.1 Temperature scenarios as monthly changes for 2050 (UKHI 2050 and CCC 2050) and for 2023 and 2060 (UKTR 3140 and UKTR 6675), referring to 1990

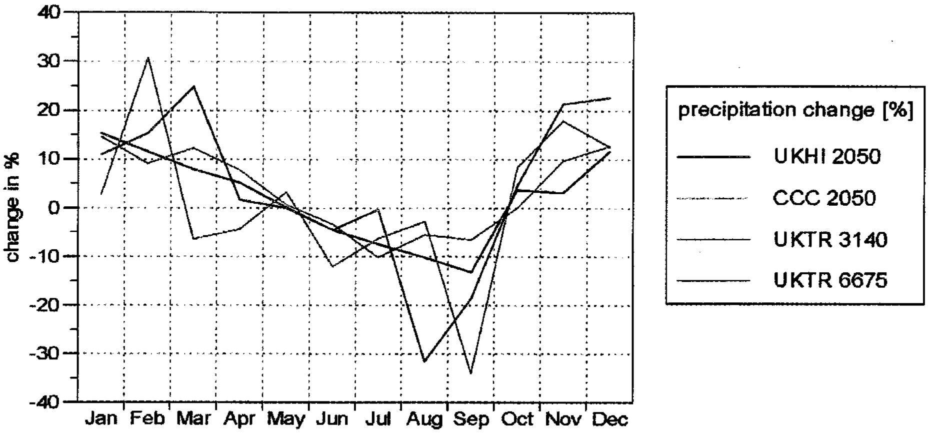


Figure 10.4.2 Precipitation scenarios as monthly changes for 2050 (UKHI 2050 and CCC 2050) and for 2023 and 2060 (UKTR 3140 and UKTR 6675), referring to 1990

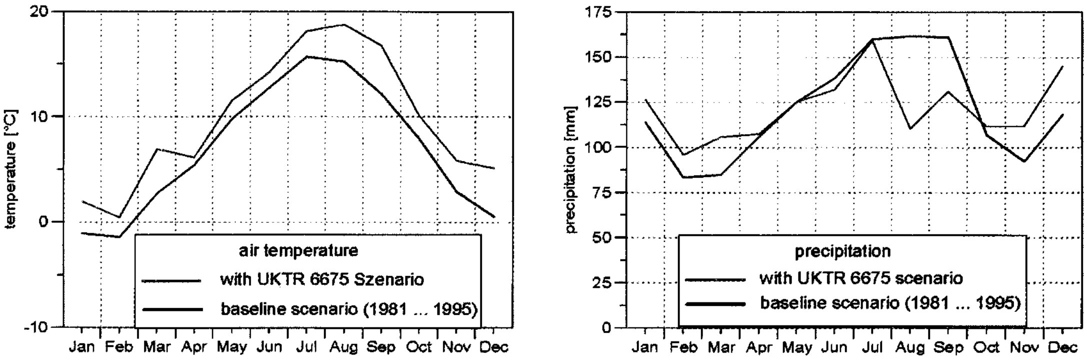


Figure 10.4.3 Mean monthly values of (a) temperature and (b) precipitation for the Thur basin; changes due to applied scenarios are shown in the red graphs

The UKHI2050 scenario

The changes shown by the UKHI scenario are of high magnitude. The annual increase in air temperature is about 2.1°C, and the monthly variation is high. In winter temperature increase is larger than in summer. A maximum temperature rise of more than 3°C is indicated in January and February. From March to July the increase continuously reduces by half, followed by a second maximum from August to October. In November the minimum increase of 1.5°C is reached. The precipitation scenario indicates an annual increase by 6.6% for the Prüm and 5% for the Blies basin. From December to April the rise has a magnitude of 10% to reach as much as 20% in January. Contrary to this, a decrease by half the scale is shown from July to September.

The UKTR6675 scenario

The UKTR6675 temperature scenario is characterised by an annual air temperature rise of about 2.4°C for the Prüm and 2.6°C for the Blies, respectively, showing significant variations from month-to-month. For the months of March, September, and December a temperature rise of 3.5°C to 4°C is indicated, the Blies value even exceeding that of the Prüm. With the exception of February, the largest increases are noted during winter and summer. The air temperature rise is much lower during the in-between seasons of spring and autumn, the minimum value in April is less than 1°C. The precipitation scenario is also very contrasting and indicates an annual change of +3% for the Prüm and +4% for the Blies. Rises of up to 30% are contrasted by decreases of nearly the same order. Maximum increase takes place in November with a second maximum in March, and the minimum occurs in August and September.

The scenarios were applied by linear transformation of the mean monthly changes to all present climate variables (air temperature, windspeed, vapour pressure, precipitation, and radiation). This method is very rough and assumes that changes in climate will also behave linear which in fact will probably not hold true. Some remarks according to the accuracy of the scenarios and the interpretation of the results have to be made. It should be mentioned that the GCM experiments on which the scenarios are based, have been examined for even coarser mesh sizes. Due to the downscaling the accuracy of the scenarios will not have increased. And even the resolution of 0.5° × 0.5° longitude/latitude does not account for regional effects. Catchments like the Prüm are as large as half the size of one grid box. The gradients within the catchment are sometimes even larger than the changes indicated by the scenarios.

Furthermore, no information is given on whether and to which extent the distribution of weather situations, the number of precipitation days and precipitation intensities have changed. Local floods in small catchments are more sensitive to changes in precipitation intensity, whereas most damaging floods within larger catchments are caused by consecutive precipitation days. It also is difficult to consider for snow conditions by shifting the present daily air temperature data by the changes in mean monthly air temperature.

10.6 Vecht catchment

The Overijsselsche Vecht catchment comprises less than four climate cells. The average changes in the climate variables for the Vecht catchment according to the eight scenarios are given in table 10.1, including annual averages as well as the values for the summer period (May to October) and the winter period (November to April). The largest changes in climate variables are predicted by the UKHI scenario. For all scenarios, the temperature increase is larger in winter than in summer. The changes in precipitation vary largely between the scenarios. Increases in precipitation in the winter period are especially large for the UKHI scenario. The annual sunshine duration reduces for all scenarios in the winter period. Average wind speed reduces in summer in the XCCC scenario, while it increases according to the UKHI scenario.

The lowland model uses the relative humidity, which is derived from the mean monthly vapour pressure (vp) that is given for each climate cell. A changed temperature in a climate change scenario induces a changed saturated vapour pressure as well. The saturated vapour pressure (svp) is computed as:

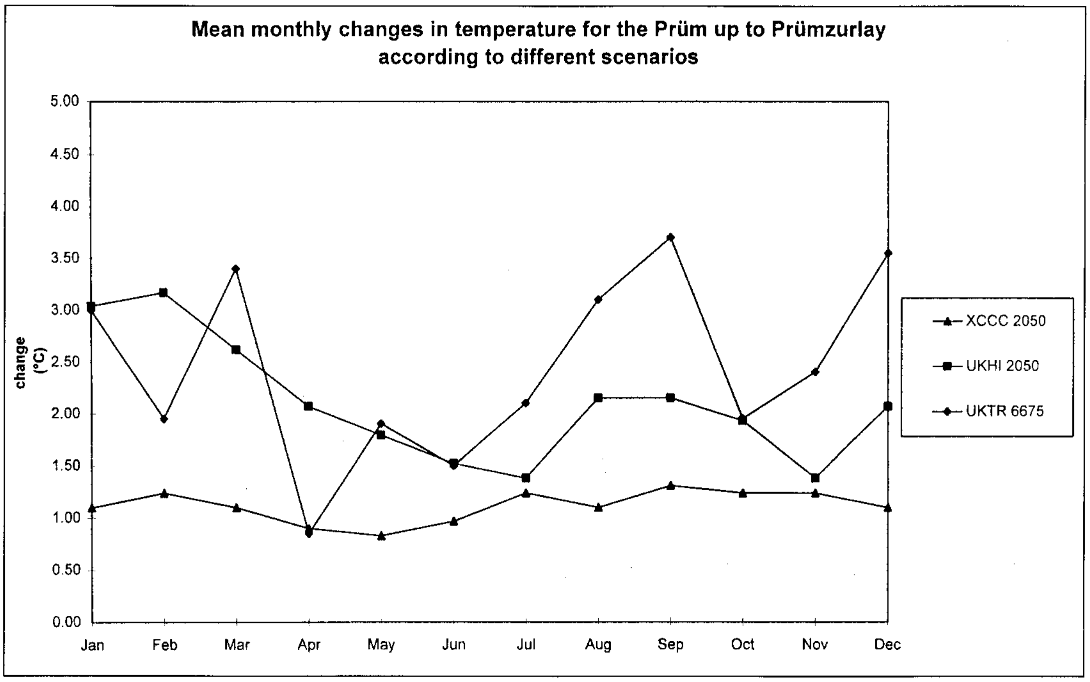


Figure 10.5.1 Mean monthly changes in temperature for the Prüm catchment according to the scenarios XCCC2050, UKHI2050, and UKTR6675 (degrees C)

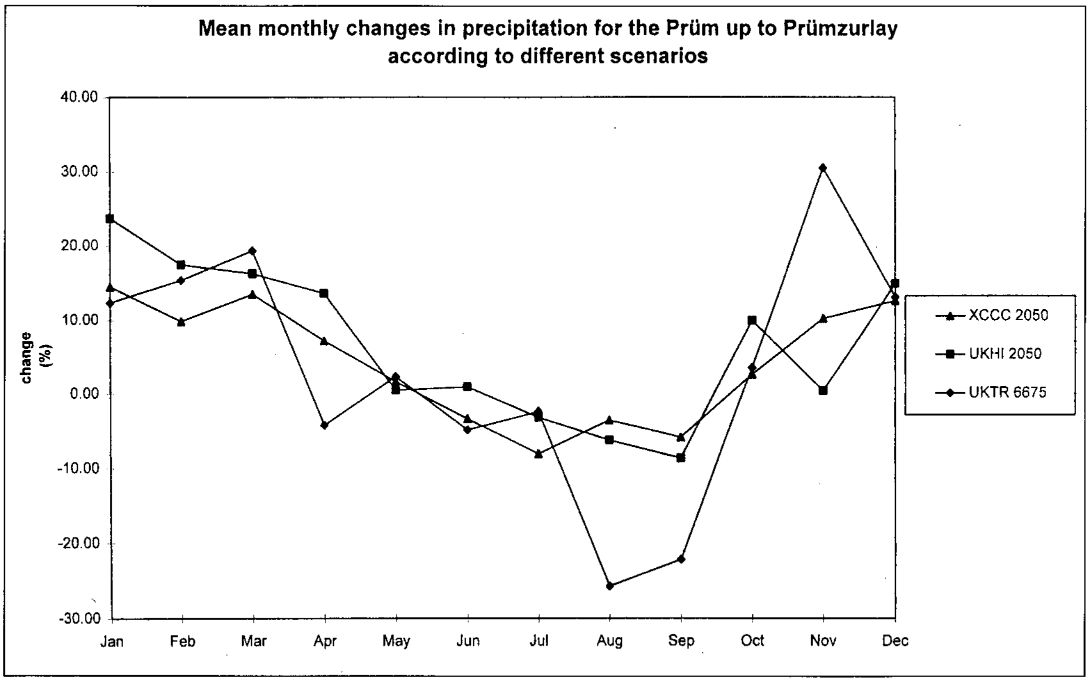


Figure 10.5.2 Mean monthly changes in precipitation for the Prüm catchment according to the scenarios XCCC2050, UKHI2050, and UKTR6675 (% change)

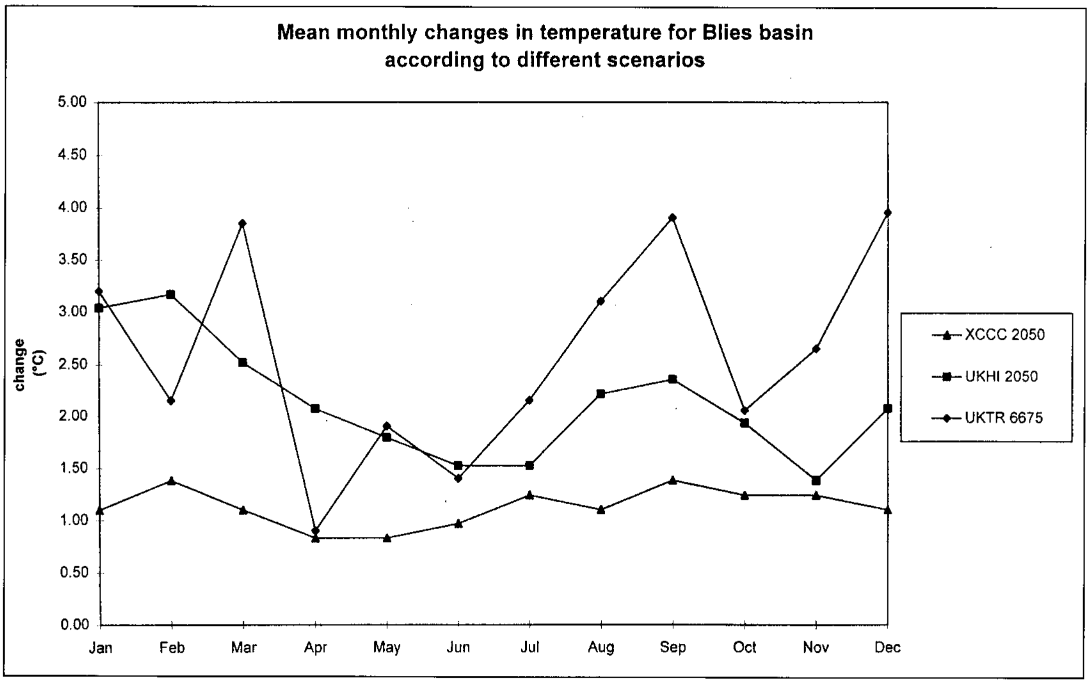


Figure 10.5.3 Mean monthly changes in temperature for the Blies basin according to the scenarios XCCC2050, UKHI2050, and UKTR6675 (degrees C)

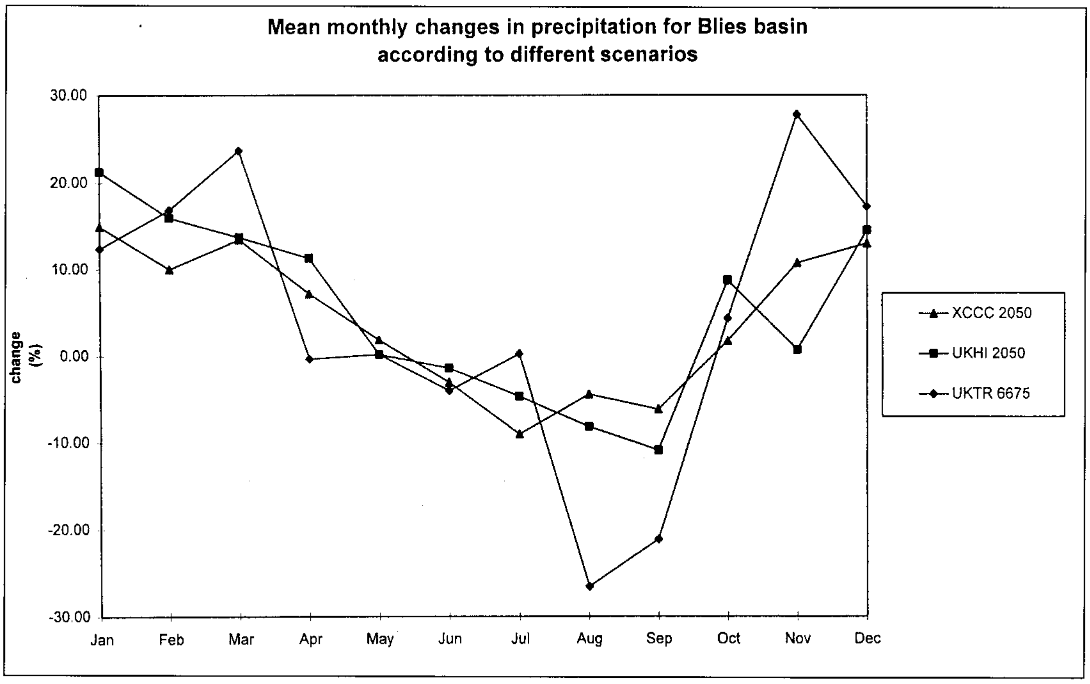


Figure 10.5.3 Mean monthly changes in precipitation for the Blies basin according to the scenarios XCCC2050, UKHI2050, and UKTR6675 (% change)

Table 10.6.1 Mean annual changes in temperature T (1^0C), precipitation P (%), sunshine hours S (%), Wind speed W (%) and Relative Humidity H (%) for the Vecht catchment. Yearly (y), Summer (s), and winter (w) changes

		ukhi 2020	ukhi 2050	ukhi 2100	xccc 2020	xccc 2050	xccc 2100	uktr 6675
T	*y*	0.9	2.0	3.8	0.5	1.0	2.0	2.3
	s	0.7	1.6	3.1	0.4	1.0	1.9	2.1
	w	1.0	2.3	4.4	0.5	1.0	2.0	2.5
P	*y*	4.9	11.0	21.3	2.1	4.8	9.3	8.9
	s	2.0	4.5	8.7	–0.2	–0.4	–0.7	–0.3
	w	7.9	17.7	34.3	4.4	10.1	19.6	18.4
S	*y*	–0.6	–1.3	–2.6	–0.1	–1.3	–1.7	–0.9
	s	1.6	3.5	6.6	0.9	2.0	4.0	6.2
	w	–2.8	–6.1	–11.8	–2.1	–4.6	–8.9	–8.0
W	*y*	1.5	3.4	6.6	–0.4	–0.9	–1.7	2.8
	s	0.9	2.0	3.8	–1.5	–3.2	–6.2	0.5
	w	2.2	4.8	9.3	0.7	1.5	2.9	5.1
H	*y*	–0.8	–2.2	–5.0	0.8	1.6	2.5	–3.8
	s	–1.1	–2.5	–5.2	0.9	1.8	2.9	–3.0
	w	–0.6	–1.8	–4.7	0.7	1.4	2.1	–4.1

$$svp = 1.3332 * e \{(17.25 * T) / (237.3 + T) + 1.51977\}$$

where T is the temperature. The change in relative humidity (rh) is calculated with the changed parameters temperature and vapour pressure by:

$$rh = vp / svp.$$

The relative humidity increases in the XCCC scenario and decreases in the UKHI and UKTR scenarios.

The present daily values of temperature, sunshine duration, wind speed, and relative humidity, are measured at the Twente meteorological station and they apply to the entire catchment. The daily record of climate parameters of the Twente station was adapted by the average monthly changes of climate parameters of the climate cells according to the scenarios. Changes in areal precipitation were applied per subcatchment.

11 Detailed description of results

11.1 Results on catchment scale

11.1.1 Murg, Ergolz and Broye catchments

11.1.1.1 Model calibration and validation

Due to the modifications in the algorithms of the IRMB model, adapted versions of the programmes were developed for optimisation of the parameters. They were run to fit the model on the observed values of the discharges. The calibration periods are not the same for the three catchments, but consist of observation periods of 6 years minimum. Table 11.1.1.1 gives various quality tests applied on the calibration period and on the verification period. The correlation coefficient ρ, the NTD Nash's quality test (Aitken, 1973), the mean relative error and the mean absolute relative error of the simulated discharges were assessed. The tests were applied on the daily values and on the monthly totals. In order to check the efficiency of the model on the extreme values, the observed and simulated monthly maxima were compared as well as the daily values during low stages.

During the verification periods, the correlation is higher than 0.91 for the three catchments and the NTD test is higher than 0.83, demonstrating good concordance of the observed and simulated discharges. The relative errors in the monthly maximum discharges show that the simulated values are underestimated. This bias is one of the typical characteristics of the daily time step models using average precipitation on

Table 11.1.1.1 Quality tests of the simulated discharges for the calibration and verification periods

	Broye catchment		Ergolz catchment		Murg catchment	
	calibration 1981-88	verification 1989-93	calibration 1983-88	verification 1989-93	calibration 1981-86	verification 1987-93
Daily discharge						
ρ	0.8598	0.9112	0.9255	0.9185	0.9107	0.9176
NTD	0.7263	0.8300	0.8530	0.8375	0.8232	0.8326
relative error	–2.5	–1.9	–3.4	4.0	–3.1	6.2
absolute relative error	29.4	26.5	26.5	29.3	23.3	24.4
Monthly discharges						
ρ	0.9176	0.9443	0.9451	0.9458	0.9607	0.9517
NTD	0.8575	0.9194	0.9143	0.9209	0.9456	0.9175
relative error	–2.5	–1.9	–3.4	4.0	–3.1	6.2
absolute relative error	15.6	15.8	16.3	17.3	11.8	13.9
Monthly maximum discharges						
relative error	–6.0	–10.3	–7.4	–6.1	–3.7	–3.2
absolute relative error	23.9	19.5	16.4	21.9	18.5	22.8
Daily discharges during low flow stages						
runoff depth	0.59 mm	0.44 mm	0.27 mm	0.24 mm	0.53 mm	0.47 mm
relative error	7.9	–4.9	9.0	22.6	–6.4	22.4
absolute relative error	21.3	20.8	32.1	40.1	20.2	29.1

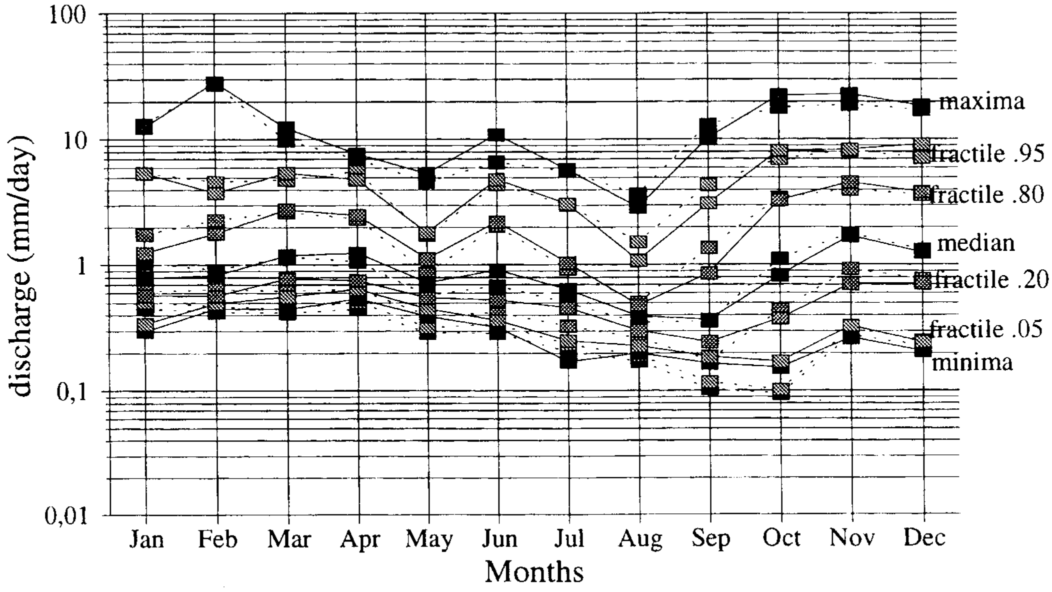


Figure 11.1.1.1 Monthly observed (continuous line) and simulated (dashed line) fractiles (percentiles) of the Broye catchment daily discharges. Verification period 1989-1993

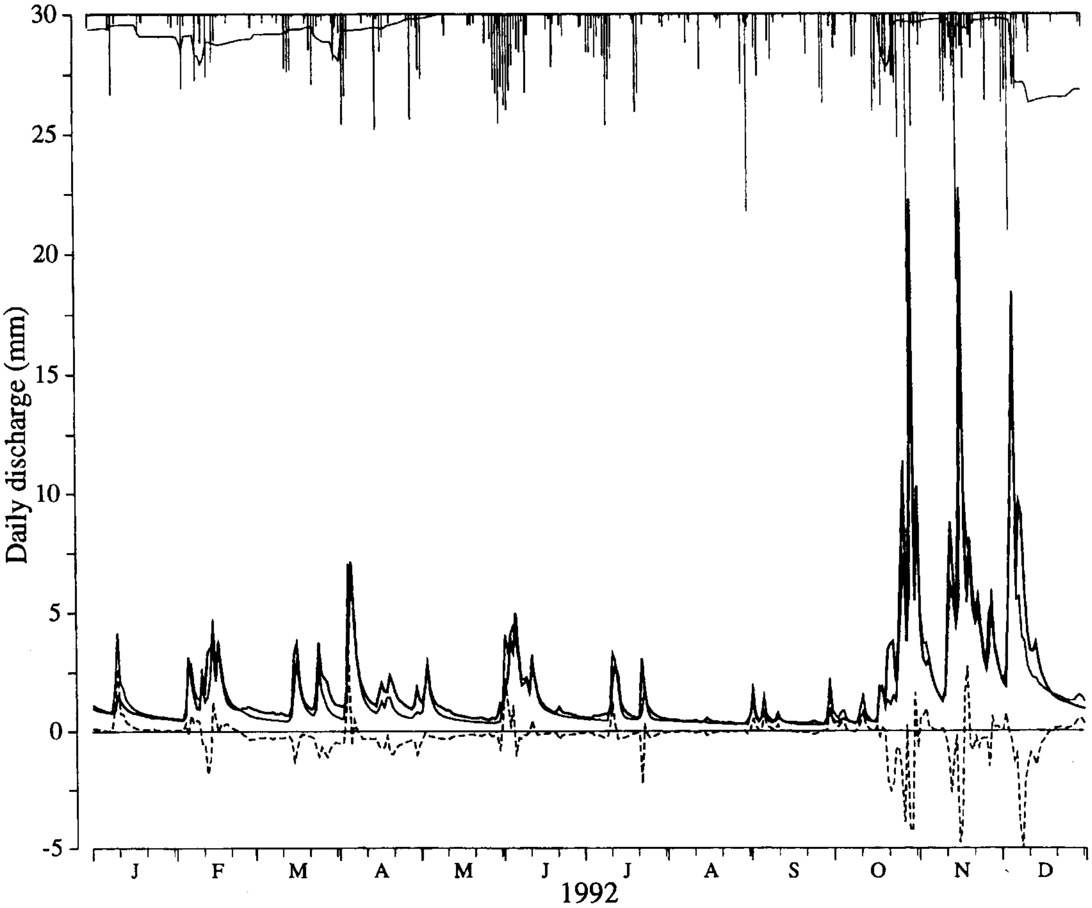


Figure 11.1.1.2 Observed (bold line) and simulated (thin line) hydrogrammes of the Broye catchment in 1992 (verification period). Difference is plotted in dashed line. Snow and rainfall on the top are reduced by 10 and 5, respectively

the catchment area. For the Broye and Murg catchments, it is interesting to note that the quality of the simulated discharges is slightly higher during the verification periods than during the calibration period. This can be related to the milder meteorological conditions during these periods.

The quality of the model can also be analysed by plotting the monthly fractiles of the daily discharges. The figure 11.1.1.1 shows this comparison for the verification periods. A trend of underestimation of the low stages has particularly become apparent during autumn. As this plot adopts logarithmic scales, the bias remains small and represents only some 0.1 mm per day. Both periods presents overestimated high values in August and September. Median values of the calibration period are not as well fitted as during the verification period confirming the global NTD and the indication of the r coefficients.

Simulated and observed hydrogrammes of selected verification years are useful in completing the study of the quality of the model. Figure 11.1.1.2 gives the observed and simulated discharges for comparison in the case of the Broye catchment in 1992. For this catchment, verification of the simulated snow cover has also taken place by using snow measurement carried out at the Moleson station, close to the upper part of the basin. This has been presented in Bultot et al. (1994).

11.1.1.2 Climate change impact on hydrology

The monthly increments describing the GC scenarios have been used to modify the daily observed data. The eight climate change scenarios have been applied directly to the data available for running the hydrological model, i.e. the 1981-1993 period. No sophisticated downscaling procedure has been introduced to disaggregate the monthly increments (absolute or relative depending on the variable) on the daily data.

Some coherence verifications on the development of water vapour pressure have been introduced in order to prevent some undesirable values, such as exceeding the saturation vapour pressure. While the scenarios have been applied to two different reference periods, i.e. the 1981-1993 period for the Broye and Murg catchments and the 1983-1993 period for the Ergolz, no specific processing has been used to 'standardise' the scenario to a common reference period. The advantage of this would be very questionable in comparison with all the other hypotheses adopted implicitly in the scenario construction. The present analysis will be mainly focused on the evolution of the mean regimes of the main components of the water cycle and on the evolution of the snow cover characteristics.

Potential evapotranspiration (PET)

The strong rise in temperature and the increase in the radiation budget are forcing the PET to show significantly higher values throughout the year (see table 11.1.1.2). These two variables dominate the decrease in wind speed and the air moisture in the XCCC experiments.

The increase of the yearly PET reaches some 20 percent in the UKHI2050 scenario (i.e. some 130 mm per year) and not even 15 percent in the XCCC2050 scenario (i.e. some 95 mm per year). The PET rise is larger in summer than in winter. In comparison with the two other catchments, the smallest rise of the winter PET is simulated in the Broye catchment. It is due to the low temperatures observed in this catchment, which remain negative in a large number of cases. Zero PET values are adopted in this case (Bultot et al., 1983). The rise of PET in the XCCC experiment is smaller than in the UKHI experiment as relative humidity slightly grows in this scenario group.

Effective Evapotranspiration

In keeping with the generalised PET growth, the effective evapotranspiration is also rising in all scenarios. Effective evapotranspiration represents almost 92 percent of the PET in present time conditions. Due mainly to the dryer conditions in summer, this ratio falls to some 89 and 86 percent, respectively, in the UKHI2050 and XCCC2050 scenarios.

Soil moisture

The depletion of water availability shown by the reduction of the ratio of effective evapotranspiration versus the PET is more salient in

Table 11.1.1.2 Monthly regimes of the potential evapotranspiration (upper row) and effective evapotranspiration (lower row) in mm per month corresponding to the present climate conditions and to the stationary UKHI and XCCC experiments and the transient UKTR experiment

	J	F	M	A	M	J	J	A	S	O	N	D	Wint	Sprin	Sum.	Autum	Year
Broye catchment																	
present	6.8	8.2	33.5	65.6	94.7	106.2	118.6	101.2	68.6	33.3	11.8	8.4	23.4	193.9	326.0	113.7	656.9
present	6.8	8.1	33.1	62.8	90.8	101.8	110.3	90.3	61.0	30.3	11.6	8.4	23.3	186.7	302.4	102.9	615.3
ukhi2050	10.2	11.6	42.2	76.6	109.1	122.3	135.8	122.2	86.0	46.1	15.1	11.8	33.7	227.9	380.3	147.3	789.2
ukhi2050	10.2	11.5	41.3	71.8	102.0	114.2	120.1	99.1	70.4	40.1	14.8	11.8	33.5	215.1	333.4	125.2	707.2
xccc2050	8.0	9.5	37.3	70.8	103.4	116.8	139.6	117.6	83.2	41.0	14.8	10.5	28.0	211.6	374.0	138.9	752.4
xccc2050	8.0	9.5	36.7	67.2	97.7	110.3	124.0	96.6	69.5	36.0	14.5	10.5	27.9	201.7	331.0	120.0	680.5
uktr2050	10.9	10.6	45.2	71.1	104.1	119.4	137.0	131.4	94.7	43.7	19.4	17.7	39.2	220.5	387.8	157.8	805.3
uktr2050	10.9	10.5	44.4	67.0	98.2	112.3	122.3	101.8	72.4	37.2	18.9	17.7	39.0	209.5	336.5	128.5	713.5
Ergolz catchment																	
present	12.5	16.4	38.7	66.1	94.8	103.8	120.2	102.9	70.7	38.0	16.0	13.4	42.3	199.7	326.9	124.8	693.7
present	12.5	16.2	38.2	64.4	90.1	98.3	107.9	88.6	60.8	33.0	15.5	13.3	42.0	192.7	294.8	109.2	638.8
ukhi2050	19.0	22.9	49.0	76.4	108.2	118.0	135.8	122.2	86.9	51.0	20.2	18.5	60.4	233.6	376.1	158.1	828.3
ukhi2050	18.9	22.4	47.7	73.9	100.8	108.9	115.2	95.8	67.2	41.5	19.0	18.3	59.6	222.4	319.9	127.7	729.6
xccc2050	15.1	18.9	42.9	70.7	102.2	112.5	139.2	117.6	83.9	46.0	19.8	16.4	50.4	215.9	369.2	149.7	785.2
xccc2050	15.1	18.6	42.1	68.7	96.3	105.1	118.8	94.0	67.0	38.0	18.8	16.2	49.9	207.2	317.9	123.8	698.8
uktr2050	20.1	21.0	52.0	71.0	102.8	114.6	136.0	131.0	95.5	49.6	26.0	27.0	68.1	225.8	381.6	171.1	846.5
uktr2050	19.9	20.6	50.7	68.8	96.6	106.6	117.1	97.2	67.9	39.5	24.2	26.6	67.1	216.1	320.8	131.6	735.6
Murg catchment																	
present	9.9	11.5	36.0	65.2	95.7	105.3	116.2	97.4	65.7	32.7	12.0	10.7	32.0	196.9	318.9	110.5	658.3
present	9.8	11.4	35.2	61.1	88.6	97.7	103.5	85.6	58.5	29.9	11.7	10.6	31.8	184.9	286.8	100.2	603.7
ukhi2050	17.5	17.8	49.2	78.0	109.9	120.0	130.3	114.8	80.6	45.1	16.5	17.6	52.9	237.2	365.2	142.2	797.5
ukhi2050	17.4	17.6	47.5	72.1	99.5	108.4	110.6	94.1	67.2	39.3	15.8	17.4	52.4	219.1	313.1	122.3	706.8
xccc2050	13.4	14.3	42.4	71.2	104.3	114.6	133.5	110.4	77.8	40.9	16.3	14.8	42.4	217.9	358.5	135.0	753.8
xccc2050	13.3	14.1	41.3	66.3	95.6	104.6	113.9	91.5	66.0	36.0	15.7	14.7	42.1	203.2	310.0	117.7	673.1
uktr2050	14.8	14.1	46.7	70.5	102.9	114.7	128.0	122.4	86.5	38.5	16.3	19.8	48.7	220.2	365.1	141.3	775.3
uktr2050	14.7	13.9	45.3	65.5	93.9	104.6	110.9	97.5	69.6	33.3	15.8	19.6	48.3	204.7	313.0	118.8	684.8

the evolution of the mean water content of the aeration zone of the soil. The soil humidity, defined as the ratio of the water content of the soil versus the maximum content of this zone, gives a normalised index allowing comparison between the different catchments. The impact of the UKHI scenario sequence on the soil moisture can be illustrated by an example. Figure 11.1.1.3 shows the increase of the humidity in late summer and autumn in the Murg catchment.

The loss of soil humidity is stronger in the UKHI scenarios than in the XCCC scenarios. For the 2050, year the yearly mean deficit represents 6 to 7 percent in the former scenario and only 4 to 5 percent in the latter. During winter the soil humidity is almost insensitive to the GC perturbations but during summer (mainly in September) it shows decreases reaching some 15 percent in the UKHI2050 scenario and some 10 percent in the XCCC2050.

The soil moisture evolution has a strong impact on the number of dry soil days, defined as the days during which the soil humidity is lower than 60 percent of its saturation value (see table 11.1.1.3). In the present climate these conditions are rather seldom: no more than 10 days per year for the Broye and the Murg catchment.

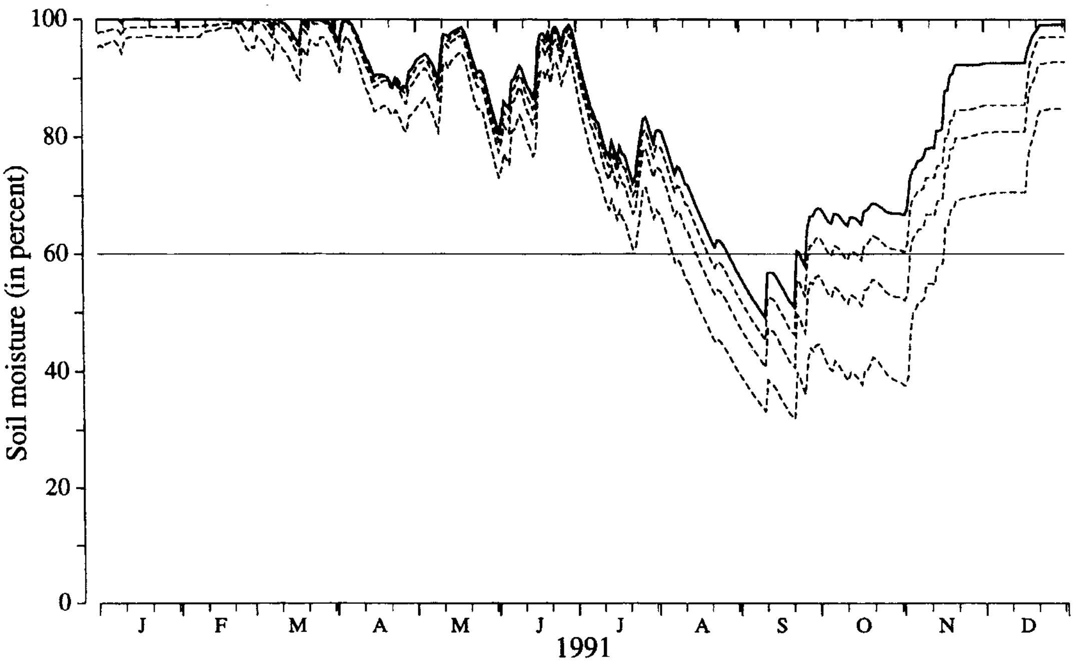


Figure 11.1.1.3 Simulated soil moisture of the Murg catchment in the present climate conditions (bold line) and in UKHI stationary experiments sequence (dashed lines)

The Ergolz catchment is the driest one, particularly in summer. The number of dry soil days is thus higher and reaches more than 30 days a year. The sensitivity of this index to the GC scenarios is very clear: in the 2050 scenarios some 40 days a year are simulated in the UKHI2050 scenario and some 35 in the XCCC2050 scenario. For the Ergolz some 90 and 80 days per year are simulated, respectively. This strong increase of conditions unfavourable to the vegetation is very important in developing the required adaptation to the GC climate evolution.

Table 11.1.1.3 Monthly regimes of the number of days during which soil moisture is lower than 60 percent and corresponding to the present climate conditions and to the stationary UKHI and XCCC experiments and the transient UKTR experiment

	J	F	M	A	M	J	J	A	S	O	N	D	Wint	Sprin	Sum.	Autum	Year
Broye catchment																	
present	0.0	0.0	0.0	0.0	0.0	0.5	1.4	3.5	3.5	3.2	0.2	0.0	0.0	0.0	5.5	6.9	12.4
ukhi2050	0.0	0.0	0.0	0.0	0.0	1.5	5.3	15.7	11.6	6.8	0.8	0.0	0.0	0.0	22.5	19.3	41.8
xccc2050	0.0	0.0	0.0	0.0	0.0	1.0	4.8	14.1	8.9	6.3	0.7	0.0	0.0	0.0	19.9	15.9	35.8
uktr2050	0.0	0.0	0.0	0.0	0.0	1.2	4.8	17.7	18.1	9.2	0.8	0.0	0.0	0.0	23.6	28.1	51.7
Ergolz catchment																	
present	0.0	0.0	0.0	0.0	0.0	0.9	2.5	11.6	10.8	7.9	3.7	0.3	0.3	0.0	15.1	22.5	37.8
ukhi2050	0.0	0.0	0.0	0.0	0.1	1.5	8.6	22.9	23.1	18.5	9.7	4.8	4.8	0.1	33.1	51.4	89.4
xccc2050	0.0	0.0	0.0	0.0	0.0	1.3	7.2	21.3	20.9	16.5	8.1	3.8	3.8	0.0	29.7	45.5	79.0
uktr2050	0.5	0.0	0.0	0.0	0.0	1.4	6.8	24.4	24.6	19.9	10.8	7.5	8.0	0.0	32.5	55.4	95.9
Murg catchment																	
present	0.0	0.0	0.0	0.0	0.0	0.0	0.8	2.9	2.2	1.7	0.0	0.0	0.0	0.0	3.7	3.8	7.5
ukhi2050	0.0	0.0	0.0	0.0	0.0	0.9	3.8	12.2	11.2	11.6	2.7	0.0	0.0	0.0	16.9	25.5	42.5
xccc2050	0.0	0.0	0.0	0.0	0.0	0.0	3.1	11.4	9.3	9.0	2.7	0.0	0.0	0.0	14.5	21.0	35.5
uktr2050	0.0	0.0	0.0	0.0	0.0	0.1	2.4	12.5	14.5	13.2	2.8	0.0	0.0	0.0	14.9	30.4	45.3

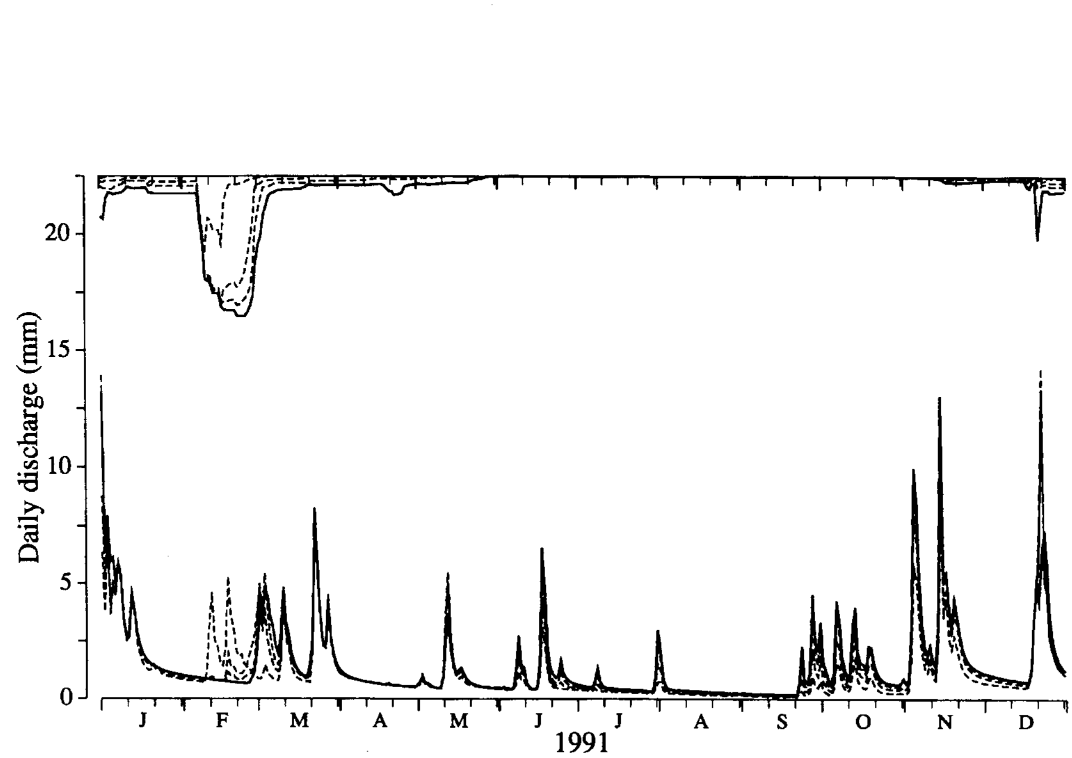


Figure 11.1.1.4 Simulated hydrogrammes of the Broye catchment in present climate conditions and in the UKHI stationary experiment sequence

Streamflow regime

The disturbed climate conditions have an effect on all the components of the water cycle. The streamflow is one of the most important as it is related to a large number of socio-economic aspects. Figure 11.1.1.4 illustrates the manifold impacts simulated in a sequence of scenarios. The disturbed snow accumulation combined with enhanced precipitation implies some modification of the winter discharges. In summer, water demand due to higher evapotranspiration induces reduction of the streamflow.

The yearly totals of streamflow summarise the evolution of the water balance at the catch-

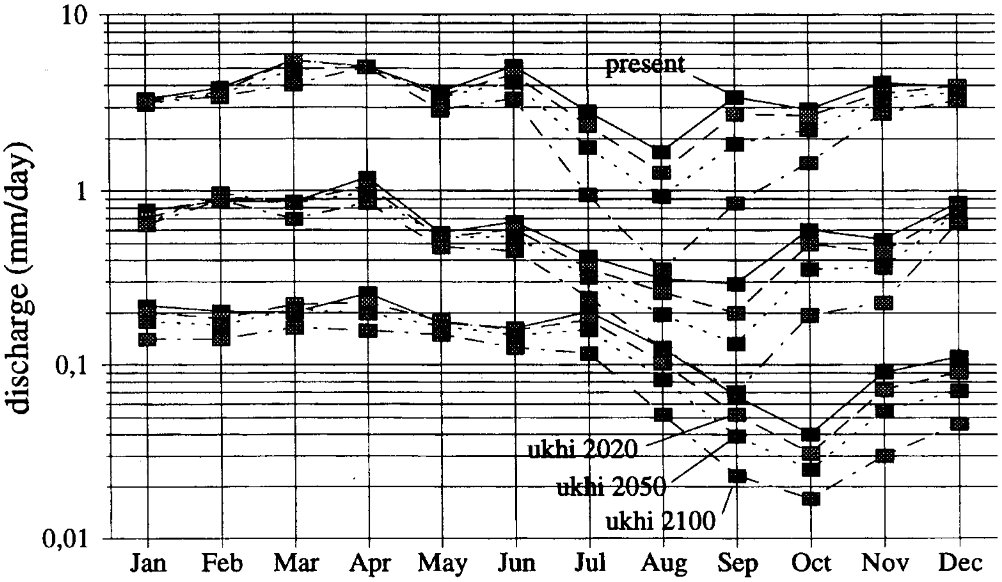


Figure 11.1.1.5 Monthly median and fractiles p0.05 and p0.95 of the daily streamflows of the Ergolz catchment in present climate conditions and in the UKHI stationary experiment

Table 11.1.1.4 Distribution indexes of the daily streamflow (in mm per day) corresponding to the present climate conditions and to the stationary UKHI and XCCC experiments, and the transient UKTR experiment

station	mean	median	max.	date max.	min.	date min.	St.dev.	p0.05	p0.95
Broye catchment 1981- 1993									
present	1.844	1.069	27.33	15/ 2/1990	0.094	5/10/1989	2.294	0.282	6.018
ukhi2050	1.677	0.943	20.39	15/ 2/1990	0.073	27/10/1989	2.116	0.214	5.656
xccc2050	1.796	1.019	24.55	6/ 1/1982	0.071	27/10/1989	2.307	0.227	6.047
uktr2050	1.671	0.930	21.52	15/ 2/1990	0.056	27/10/1989	2.160	0.199	5.685
Ergolz catchment 1983- 1993									
present	1.146	0.608	18.27	27/ 9/1987	0.024	3/11/1985	1.437	0.120	3.961
ukhi2050	0.945	0.473	15.63	4/ 4/1992	0.016	3/11/1985	1.249	0.069	3.424
xccc2050	1.061	0.544	16.84	4/ 4/1992	0.017	3/11/1985	1.394	0.082	3.788
uktr2050	0.940	0.457	15.25	4/ 4/1992	0.017	3/11/1985	1.295	0.058	3.445
Murg catchment 1981- 1993									
present	1.575	0.994	17.77	10/ 4/1986	0.060	24/11/1983	1.691	0.297	4.730
ukhi2050	1.345	0.797	18.36	30/ 1/1982	0.100	24/11/1983	1.604	0.234	4.307
xccc2050	1.475	0.869	21.10	30/ 1/1982	0.116	3/11/1985	1.764	0.260	4.700
uktr2050	1.446	0.842	20.53	16/12/1981	0.080	23/11/1983	1.795	0.225	4.665

ment scale. As the increase of the effective evapotranspiration simulated under the GC conditions is greater than the precipitation increase, all the yearly streamflows are decreasing. The decrease in the UKHI2050 scenario is reaching some 17 percent in the Ergolz and the Murg catchments (by 74 and 84 mm per year, respectively), but only 9 percent (61 mm per year) in the Broye catchment. This smaller sensitivity of the Broye streamflow can also be found in its response to the XCCC scenarios but not to the UKTR scenarios. The reason behind this behaviour is not obvious; larger temperature rises are proposed in these scenarios during particular months of the cold season (i.e. December and March in the UKTR2050) and are probably interacting with the snow cover, which is more important in the Broye catchment (see chapter 11.1.1.3). Most of the simulations present at least one winter month with a streamflow rise and most of the total winter streamflows are increasing. This rise consists in a few centimetres in the Broye, and to a smaller extent in the Murg, but only a few tens of millimetres in the Ergolz catchment.

Streamflow statistical characteristics

The statistical characteristics of the daily streamflow can be described by several indexes. The mean and the median give the central position of the distribution, while the dispersion can be illustrated by the standard error or deviation. As concerns the extreme values, the most popular indexes are the fractiles corresponding to the probability 0.05 and 0.95 and giving the low flow and the flood thresholds, respectively. Table 11.1.1.4 gives the values of these statistics in the different scenarios, with the simulated daily extreme values.

As the streamflow distributions are asymmetric, the median values are smaller than the mean values. In all the scenarios, the mean daily streamflow and the median are decreasing. The 0.05 fractiles, $p_{0.05}$, are following the same decrease; the absolute minima simulated are also reduced in the GC conditions, except in the Murg catchment. As concerns the high values, the 0.95 fractiles, $p_{0.95}$, are smaller in the GC conditions, except in the XCCC2050 and XCCC2100 scenarios for the Broye catchment. The peak values simulated for the reference period are smaller in the Ergolz catchment and greater in the Murg catchment. For the Broye catchment, higher or lower maximum values have been simulated, depending on the scenario. The use of this information based on only one value is not easy and must be exercised with caution. This is supported by the fact that, for most of the scenarios, the date of peak values differs from that of the present climate.

Table 11.1.1.5 Seasonal regimes of the number of flood days and of low flow days corresponding to present climate conditions and to the stationary UKHI and XCCC experiments, and the transient UKTR experiment

	Number of flood days					Number of low flow days				
	Winter	Spring	Sum.	Autumn	Year	Winter	Spring	Sum.	Autumn	Year
Broye catchment										
present	5.5	6.1	1.2	5.4	18.2	1.3	0.0	6.2	10.6	18.2
ukhi2050	7.8	4.4	0.4	3.2	15.7	1.5	0.0	11.3	21.4	34.2
xccc2050	8.0	5.9	0.6	3.8	18.3	1.3	0.0	10.2	16.7	28.2
uktr2050	6.8	5.8	0.4	2.7	15.8	1.4	0.0	11.0	27.4	39.8
Ergolz catchment										
present	3.6	7.6	3.1	3.8	18.2	1.9	0.0	1.2	15.2	18.3
ukhi2050	2.7	6.5	1.8	1.8	12.9	2.8	0.0	7.4	29.1	39.3
xccc2050	3.9	8.0	2.3	2.7	16.9	2.4	0.0	5.9	24.6	32.9
uktr2050	2.1	7.3	2.2	1.9	13.5	3.6	0.0	9.0	34.2	46.8
Murg catchment										
present	5.8	5.2	2.4	4.8	18.2	0.0	1.8	5.1	11.2	18.1
ukhi2050	6.5	4.4	1.2	2.1	14.2	1.2	2.5	11.2	21.9	36.8
xccc2050	7.5	6.2	1.3	2.9	17.9	0.4	1.5	7.9	18.2	28.0
uktr2050	7.6	5.9	1.5	2.5	17.5	0.5	1.8	8.9	24.7	35.9

The evolution of the standard deviation shows a reduction of the range of the streamflow values in the Ergolz catchment, in accordance with the smaller high values simulated. The UKHI scenarios also produce the same trend in the Broye and Murg catchments, as does the UKTR in the Broye catchment.

The monthly evolution of the $p_{0.05}$ fractile, of the median and of the $p_{0.95}$ fractile gives a clear picture of the dispersion of the daily streamflows under the GC conditions. Figure 11.1.1.5 illustrates the case of the Ergolz catchment in the UKHI experiments. The lowest values of those three indexes are out of phase; the minimum of the high stages (fractile 0.95) is simulated in August, while the minimum median (fractile 0.50) is in September and the minimum of the low stages (fractile 0.05) is in October. This figure shows the strengthening of the GC impact on the streamflow characteristics, with the time lag.

Floods and low flows

When defining the flood days as days during which the streamflow is higher than the $p_{0.95}$ fractile of the daily streamflow simulated in the present climate, it is interesting to compare the evolution of the flood occurrence under the GC conditions. Table 11.1.1.5 shows the clear yearly decrease of the flood spells in the GC scenarios, except for the particular XCCC2050 scenario in the Broye catchment. The study of the seasonal number of flood days indicates a strong decrease in the warm seasons, but an increase in the number of flood days occurs in winter or in some cases in spring for the Broye and Murg catchments. This tends to produce more contrasted streamflow regimes with more floods in winter but no higher stages and lower stages in summer.

The study of the evolution of the low flow periods follows the same method and is based on the analysis of the number of days during which the streamflow is lower than the $p_{0.05}$ fractile assessed in the present climate (see table 11.1.1.4). Table 11.1.1.5 shows the obvious rise of low stage days for all the catchments. In the warmer-dryer UKHI050 scenario, this rise corresponds to more than twice the present 18 days a year. Except in some particular cases, this rise occurs during all the seasons.

Table 11.1.1.6 Seasonal regimes of the mean maximum and minimum of the daily streamflow corresponding to present climate conditions and to the stationary UKHI and CCC experiments, and the transient UKTR experiment

	Mean seasonal maximum (mm/day)					Mean seasonal minimum (mm/day)				
	Winter	Spring	Sum.	Autumn	Year	Winter	Spring	Sum.	Autumn	Year
Broye catchment										
present	15.53	12.36	5.52	11.72	17.80	0.58	0.58	0.34	0.31	0.27
ukhi2050	15.51	9.94	3.78	9.61	15.62	0.62	0.60	0.27	0.21	0.20
xccc2050	16.92	11.65	4.33	10.64	17.20	0.63	0.63	0.29	0.23	0.22
uktr2050	15.65	11.34	4.02	9.31	16.17	0.58	0.61	0.27	0.17	0.17
Ergolz catchment										
present	6.39	8.37	6.14	6.22	10.80	0.22	0.26	0.18	0.14	0.12
ukhi2050	5.32	7.85	4.78	4.48	8.92	0.21	0.25	0.13	0.08	0.07
xccc2050	6.02	8.60	5.18	5.20	10.02	0.23	0.28	0.14	0.09	0.08
uktr2050	5.16	8.04	5.09	4.62	9.06	0.19	0.26	0.11	0.06	0.06
Murg catchment										
present	10.12	8.46	6.05	8.23	12.47	0.52	0.44	0.31	0.37	0.25
ukhi2050	9.84	8.48	4.37	5.76	12.52	0.47	0.44	0.27	0.25	0.19
xccc2050	10.70	9.40	4.74	6.65	13.68	0.47	0.50	0.25	0.20	0.17
uktr2050	10.96	9.29	4.85	6.16	13.57	0.49	0.47	0.28	0.21	0.18

Table 11.1.1.6 contributes to the description of the evolution of the extreme values: higher mean maxima in winter for the Broye and Murg catchments only in the UKHI and UKTR experiments, and a smaller mean winter maximum for the Ergolz catchment; smaller summer and autumn mean maxima for all the catchments. Some mean spring maxima show slight growth (Murg catchment and XCCC experiment for the Ergolz catchment), but not that much. In accordance with the evolution of the absolute maximum streamflow presented in Table 11.1.1.4, the mean yearly maximums are growing in the Murg catchment and decreasing in the two other catchments.

The decrease of the mean yearly minimum streamflow is generalised, as is the decrease during summer and autumn. During winter and spring, seasonal mean minimum values can either grow or decrease, depending on the scenario. Low discharges will thus be more numerous and lower than in the present climate, on average.

Global change impacts on the streamflow characteristics are thus manifold. As far as the high values are concerned, the decrease in the number of flood days can be positive for safety of the population. However, it should be noted that final conclusions on real peak flow changes could only be made in these catchments by using hydrological models with a time resolution of one hour, while also knowing more about rainfall intensity distribution. However, results from Schulla (see chapter 11.1.2 in this report) using an hourly simulation in the Murg catchment confirm the results presented here.

As far as the well pronounced decrease in the streamflow in the warm season is concerned, a reduction of the water availability is possible in the future. This implies not only a reduction in the water quantity available for human needs but also for agriculture and industry. Impacts on the water quality can also be feared.

11.1.1.3 Interpretations of selected scenario results

The daily values of the snow cover water equivalent have been simulated for the three catchments by using the altitude slices proce-

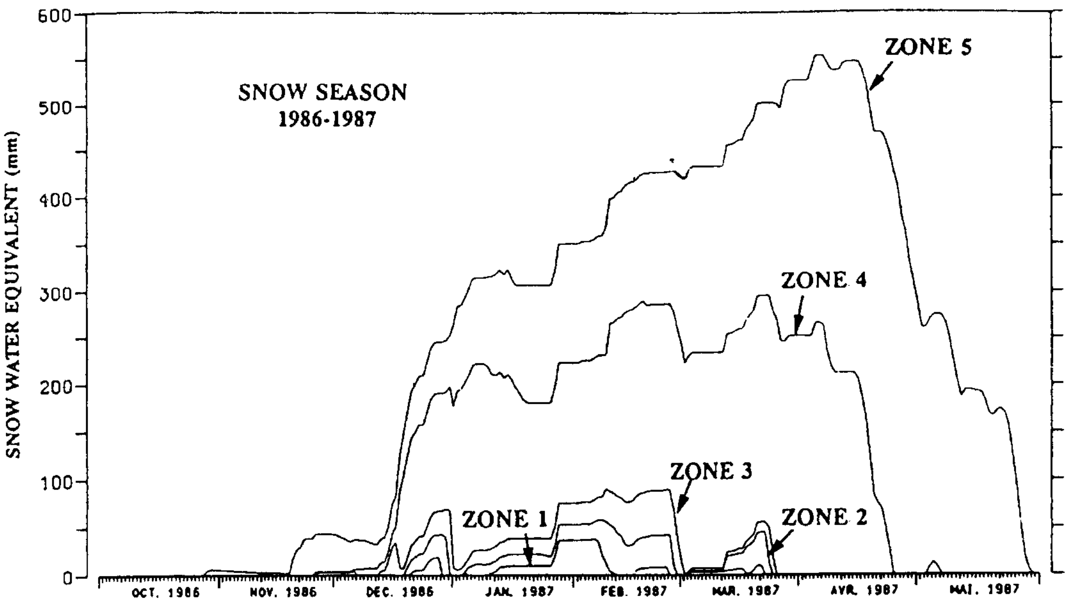


Figure 11.1.1.6 Simulated snow cover water equivalent of the Broye catchment for the 5 reference altitude slices in present climate. (zone 1: below 600 m, zone 2: 600 - 700 m, zone 3: 700 - 900 m, zone 4: 900 - 1200 m and zone 5: 1200 - 1500 m)

dure. The water equivalent of the snow cover assessed for the five reference altitude zones of the Broye catchment have been illustrated in figure 11.1.1.6. Great differences are simulated between the lowest zone where a maximum of 50 mm is reached at the end of January while the maximum of the upper zone reaches more than 500 mm in April. The study dealing with the Broye catchment and presented in Bultot et al. (1994) gives additional details about the snow cover characteristics at the different altitude ranges.

Figure 11.1.1.7 illustrates the averaged values of the snow layer integrated over the whole area of the Broye catchment in the scenarios corresponding to the UKHI experiments. The higher temperature in the GC conditions is mainly reducing the thickness of the snow cover and shortening its time duration. As shown in table 11.1.1.7, the temperature rise impact is dominant for all the scenarios and catchments. The rather low values given in this table are due to the fact that the averaged snow equivalents are assessed for both the low altitude regions

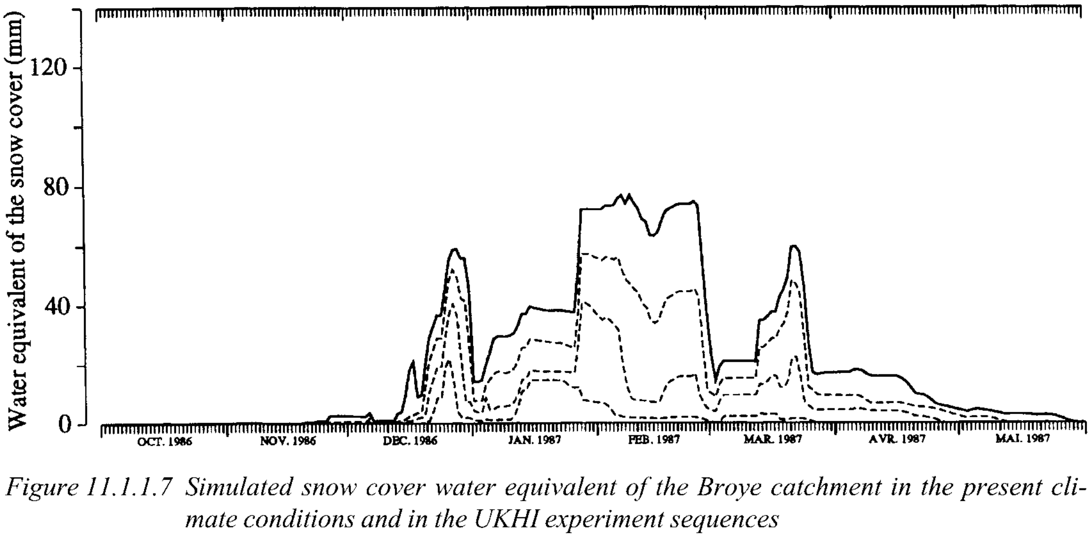


Figure 11.1.1.7 Simulated snow cover water equivalent of the Broye catchment in the present climate conditions and in the UKHI experiment sequences

Table 11.1.1.7 Monthly regimes of the snow cover water equivalent integrated over all catchments and corresponding to the present climate conditions and to the stationary UKHI and XCCC experiments, and the transient UKTR experiment

	J	F	M	A	M	J	J	A	S	O	N	D	Wint	Spr	Sum.	Aut	Year
Broye catchment																	
present	29.5	52.4	45.2	11.7	2.2	.0	.0	.0	.0	0.4	2.8	20.9	34.2	19.7	.0	1.1	13.8
ukhi2050	10.0	13.1	10.7	1.8	0.2	.0	.0	.0	.0	.0	1.3	6.6	9.9	4.3	.0	0.4	3.7
xccc2050	18.0	27.5	22.0	4.5	0.8	.0	.0	.0	.0	.0	1.4	9.3	18.3	9.1	.0	0.5	7.0
uktr2050	10.8	22.9	16.2	2.6	0.4	.0	.0	.0	.0	.0	0.9	2.3	12.0	6.4	.0	0.3	4.7
Ergolz catchment																	
present	5.4	9.5	10.5	0.3	.0	.0	.0	.0	.0	.0	1.3	4.6	6.5	3.6	.0	0.4	2.6
ukhi2050	2.3	3.8	3.2	.0	.0	.0	.0	.0	.0	.0	0.7	1.1	2.4	1.1	.0	0.2	0.9
xccc2050	3.8	6.8	7.3	0.1	.0	.0	.0	.0	.0	.0	0.8	2.5	4.4	2.5	.0	0.3	1.8
uktr2050	1.9	6.3	4.9	0.1	.0	.0	.0	.0	.0	.0	0.6	0.2	2.8	1.7	.0	0.2	1.2
Murg catchment																	
present	12.0	12.8	9.8	0.3	.0	.0	.0	.0	.0	.0	1.5	5.1	10.0	3.4	.0	0.5	3.5
ukhi2050	5.1	3.6	2.3	.0	.0	.0	.0	.0	.0	.0	1.0	0.9	3.2	0.8	.0	0.3	1.1
xccc2050	8.7	7.0	5.5	0.1	.0	.0	.0	.0	.0	.0	1.3	1.7	5.8	1.9	.0	0.4	2.0
uktr2050	6.3	6.9	3.2	0.1	.0	.0	.0	.0	.0	.0	0.6	0.3	4.5	1.1	.0	0.2	1.5

and the upper part of the catchments. Thick snow cover in the latter (see figure 11.1.1.6) is not large enough to offset the low value in the valley; in addition these low altitudes represent a larger part of the basins than the highest one.

The purpose of the present report is to draw the picture of the sensitivity of the snow layer to the GC conditions. For this reason, the text focuses on the average regime of the snow water equivalent integrated over the three catchments. These regimes are given in table 11.1.1.7. The number of days during which snow cover has been simulated for at least one altitude slice of the catchment has also been studied. This number of snow days is presented in table 11.1.1.8. As a consequence of its warm character, the UKHI2100 scenario produces the strongest reduction of the snow cover. In this case, the water equivalent is reduced by almost 10 per cent in winter, while the XCCC projection for the year 2100 implies a mere 50 per cent reduction in winter.

As shown in figure 11.1.1.7 for a particular winter season, the reduction of the number of snow days is also dramatic. The snow periods simulated for the three catchments in the UKHI2100 scenario are at least $2^1/_2$ months shorter, while the diminution is smaller in the XCCC2100, at only $1^1/_2$ months. When limited to the year 2020, the reduction rates to a minimum of around 20 days.

The important snow field reduction has some impacts on the characteristics of the streamflow. The major floods occurring in winter or in spring, caused by the combination of precipitation and snow melting, are generally smaller in the GC conditions. The decrease in the $p_{0.95}$ fractiles (table 11.1.1.4) and of the yearly mean maximum (table 11.1.1.6) of the Broye and Ergolz illustrates this evolution while the mean winter maxima of these catchments show a small increase in some scenarios. In the Murg catchment, where infiltration is lower than in the Ergolz catchment, the rise of the precipitation amount seems to dominate the snow field reduction.

11.1.2 Thur catchment

11.1.2.1 Model calibration and validation

The time period used in this part of the study is that of 1981 to 1995. Air temperature, precipitation, relative sunshine duration, global radiation, wind speed and vapour pressure were

Table 11.1.1.8 Monthly regimes of the number of snow days corresponding to the present climate conditions and to the stationary UKHI and XCCC experiments, and the transient UKTR experiment

	J	F	M	A	M	J	J	A	S	O	N	D	Wint	Spr	Sum.	Aut	Year
Broye catchment																	
present	29.7	28.2	31.0	29.2	16.8	0.5	.0	.0	.0	4.1	22.9	29.3	87.2	77.0	0.5	27.0	191.8
ukhi2020	29.2	28.2	31.0	25.9	9.5	.0	.0	.0	.0	3.5	17.5	28.5	85.8	66.5	.0	21.0	173.3
ukhi2050	27.8	27.6	28.2	17.2	3.3	.0	.0	.0	.0	2.2	14.1	27.9	83.4	48.7	.0	16.3	148.4
ukhi2100	21.8	19.7	17.7	2.2	.0	.0	.0	.0	.0	.0	8.5	21.7	63.2	19.8	.0	8.5	91.5
xccc2020	29.6	28.2	31.0	27.9	12.8	.0	.0	.0	.0	3.8	18.0	29.3	87.2	71.8	.0	21.8	180.8
xccc2050	29.2	28.2	30.6	25.1	7.5	.0	.0	.0	.0	3.2	14.8	28.2	85.6	63.2	.0	17.9	166.8
xccc2100	28.0	28.0	27.8	18.2	3.4	.0	.0	.0	.0	1.3	11.6	27.1	83.1	49.5	.0	12.9	145.5
uktr2020	31.0	27.1	30.1	25.5	10.3	.0	.0	.0	.0	3.7	14.2	30.0	88.1	65.9	.0	17.9	171.9
uktr2050	27.9	28.2	30.2	24.2	5.6	.0	.0	.0	.0	2.3	9.5	24.7	80.8	59.9	.0	11.8	152.6
Ergolzcatchment																	
present	22.7	23.5	18.9	7.2	0.5	.0	.0	.0	.0	2.7	9.5	20.5	66.8	26.5	.0	12.3	105.6
ukhi2020	18.8	19.7	15.9	4.5	0.2	.0	.0	.0	.0	0.4	8.8	17.3	55.8	20.5	.0	9.2	85.5
ukhi2050	13.7	14.5	10.5	1.6	.0	.0	.0	.0	.0	.0	5.9	11.3	39.5	12.2	.0	5.9	57.6
ukhi2100	5.2	8.5	5.1	0.5	.0	.0	.0	.0	.0	.0	4.0	6.8	20.5	5.5	.0	4.0	30.1
xccc2020	21.0	22.3	17.5	5.9	0.2	.0	.0	.0	.0	1.5	8.9	19.0	62.3	23.6	.0	10.5	96.4
xccc2050	18.7	19.4	15.8	4.3	0.2	.0	.0	.0	.0	0.3	5.9	15.2	53.3	20.3	.0	6.2	79.7
xccc2100	14.8	14.5	11.9	1.9	.0	.0	.0	.0	.0	.0	4.6	11.1	40.4	13.8	.0	4.6	58.8
uktr2020	19.7	12.0	15.1	3.6	0.3	.0	.0	.0	.0	.0	5.2	20.6	52.4	19.0	.0	5.2	76.5
uktr2050	13.3	18.1	12.0	4.9	.0	.0	.0	.0	.0	.0	4.0	7.6	39.0	16.9	.0	4.0	59.9
Murgcatchment																	
present	27.2	26.5	22.7	10.2	0.6	.0	.0	.0	.0	2.6	15.3	25.8	79.5	33.5	.0	17.9	130.8
ukhi2020	23.5	23.9	18.1	2.8	.0	.0	.0	.0	.0	0.8	12.9	21.9	69.3	20.9	.0	13.7	103.9
ukhi2050	19.2	18.6	10.4	1.5	.0	.0	.0	.0	.0	.0	10.8	18.0	55.8	11.8	.0	10.8	78.5
ukhi2100	9.6	9.0	4.7	0.3	.0	.0	.0	.0	.0	.0	5.7	8.5	27.2	5.0	.0	5.7	37.8
xccc2020	25.4	25.7	20.5	6.6	0.3	.0	.0	.0	.0	1.0	12.7	23.2	74.3	27.4	.0	13.7	115.4
xccc2050	22.9	24.1	17.8	2.8	.0	.0	.0	.0	.0	0.6	11.2	20.7	67.7	20.7	.0	11.8	100.2
xccc2100	19.2	18.6	11.3	1.6	.0	.0	.0	.0	.0	.0	6.7	15.8	53.6	12.9	.0	6.7	73.2
uktr2020	24.8	17.4	18.2	2.8	0.3	.0	.0	.0	.0	0.2	7.5	25.7	67.9	21.3	.0	7.7	96.9
uktr2050	19.7	22.8	14.2	2.7	.0	.0	.0	.0	.0	.0	5.8	10.3	52.8	16.9	.0	5.8	75.6

used as meteorological input data in an hourly resolution (for the number and the location of the meteorological stations see chapter 7, table 7.1 and fig. 8.2.1). Further, the 100 m × 100 m land use database (for derivation of vegetation properties such as leaf area index, stomatal resistance, aerodynamic resistance), the 250 m × 250 m digital elevation map of Switzerland (elevation, slope, aspect, topographic index) and a digitised soil map (derivation of porosity, hydraulic conductivity, wilting point, field capacity, soil topographic index) were used to run the model. For model calibration the year 1984 was chosen at random. The years 1981 to 1995 were used for validation. All model runs for the Thur basin were carried out with a spatial resolution of 500 m × 500 m and with a temporal resolution of one hour. For the calibration procedure only observed discharge values were used, no other internal state variables, like groundwater table, were available for comparison with modelled variables.

The meteorological data was interpolated using altitude dependent regression with an areal regression fitting the residuals for the variables air temperature, wind speed, global radiation and vapour pressure. Sunshine duration was interpolated using inverse distance weighting interpolation (IDW) only, whereas precipitation was interpolated using 25% of an altitude dependent regression and 75% of IDW interpola-

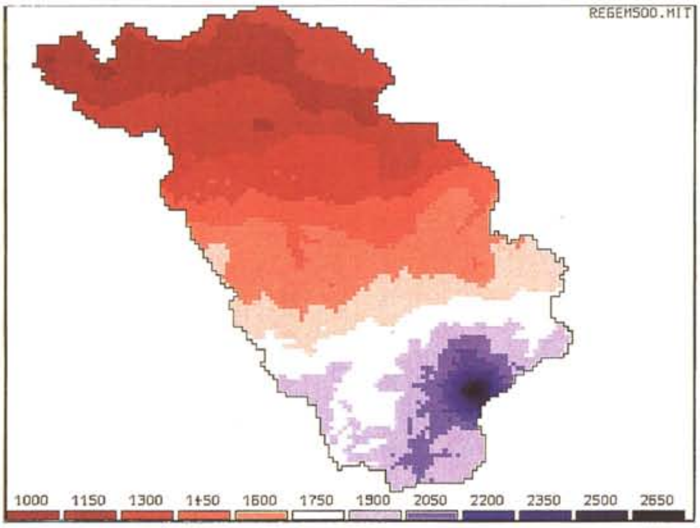


Figure 11.1.2.1 Mean yearly precipitation for the Thur basin as calculated by combined altitude dependent and inverse distance weighting interpolation (low values in the lower parts, high values in the upper parts – peak: Säntis 2709 mm (2504 m a.s.l.), mean 1450 mm)

tion as weighting factors. The altitude dependent regression is able to consider one or two inversions in the atmosphere. Typical altitudes for such inversions were chosen at 800 and 1400 m as being representative for the Thur basin. Altitudinal gradients were estimated for each time interval, using actual data. The inversion lines (if applicable) were also estimated from actual data using the default values and the estimated actual gradients. Methods and parameters for interpolation were not changed for all scenario runs and the control run. An example of a combination of inverse distance interpolation (75%) and altitude dependent regression (25%) of precipitation is shown in figure 11.1.2.1. It gives the mean yearly precipitation for the Thur basin for the years 1981 to 1995.

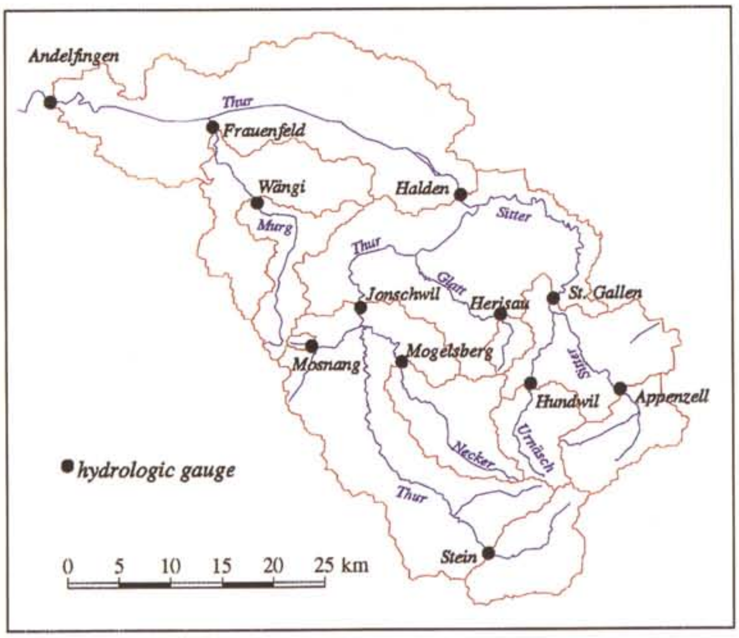


Figure 11.1.2.2 The Thur Basin structure with its subcatchments and gauging stations

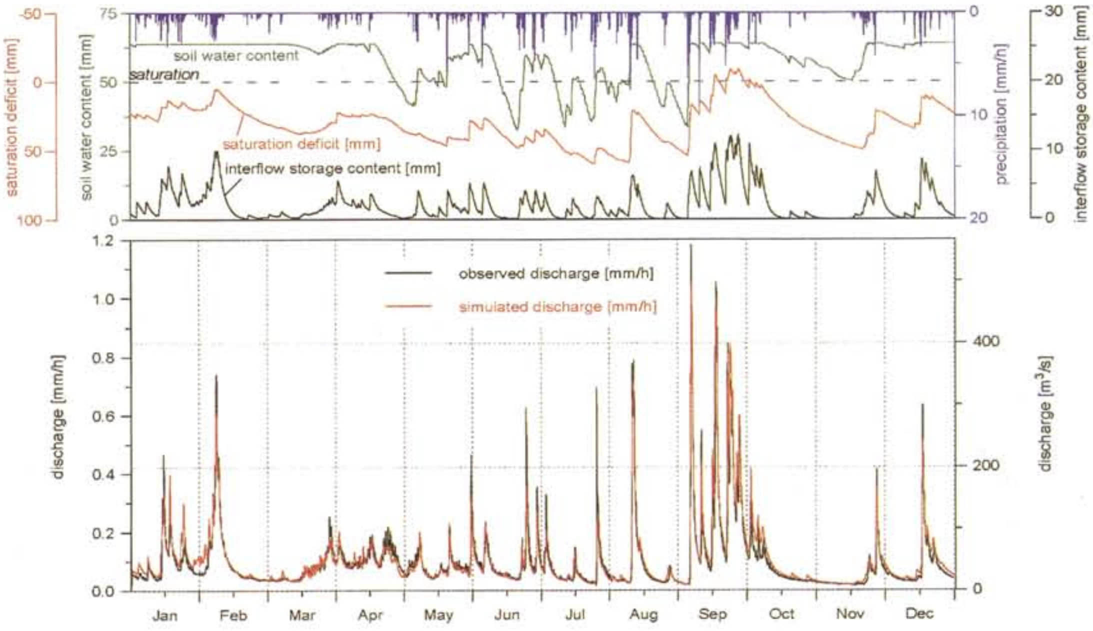


Figure 11.1.2.3 Results of the calibration run for the Thur basin for 1984; the upper part shows the temporal course of precipitation and the internal state variables soil water content, saturation deficit and interflow storage content, the lower part shows simulated and observed discharges for gauge Andelfingen (entire Thur basin, $EV_{lin} = 0.924$, $r^2_{lin} = 0.922$)

For the calibration run, initial states of the internal variables, saturation deficit, and interflow storage content, were found by trial and error (comparison with discharge). Unsaturated zone storage, interception storage and snow storage were assumed to be empty as the initial state, soil water storage was assumed to be full (soil water content at field capacity). The strong variations in topography within the basin and the strong altitude dependence of climate variables, land uses and soil characteristics were the reasons for the subdivision of the basin into 12 subbasins with areas ranging from 3.3 km^2 up to 406 km^2, all of them delineated with respect to a hydrologic gauging station. Thus a spatially more detailed calibration / validation procedure was possible. Figure 11.1.2.2 shows this structure of the Thur basin.

The parameters for the model components were derived from measurements (e.g. recession parameter m for the runoff generation model or the relation between global radiation, sunshine duration and longwave radiation), from maps (some soil properties), from literature (e.g. stomatal resistances from Thompson et al., 1981; snow melt and accumulation parameters from Anderson, 1973 and Braun, 1985; interception parameters from Gurtz, 1988 and Münch, 1993; soil parameters from Brakensiek et al., 1981) or by calibration (e.g. flow routing parameters, soil transmissivity correction factors).

The results from the calibration run are shown in figure 11.1.2.3. All internal state variables and the precipitation graph are areal means for the entire Thur basin. The performance criteria show very high values with $EV_{lin} = 0.924$ and $r^2_{lin} = 0.922$ for the linear and $EV_{ln} = 0.924$ and $r^2_{ln} = 0.914$ for the logarithmic simulation results, according to the discharges at gauge Andelfingen/Thur. In the 11 subbasins too, the criteria show high values between 0.72 and 0.90 for logarithmic and between 0.68 and 0.91 for linear results. Only the subbasin of gauge Herisau (river Glatt) with an area of approximately 20% used for settlements shows an $EV_{lin} = 0.4$ and $EV_{ln} = 0.73$. The difference between these values indicates errors, particularly in the peak flood simulation, may be caused by the land use distribution in this catchment.

The simulated hydrograph represents the

Table 11.1.2.1 Calibration results for the Thur and its 11 subcatchments, 1984, modelled in hourly resolution, spatial resolution 500 x 500 m^2. EV_{lin} , EV_{ln} = explained variance coefficients and r^2_{lin}, r^2_{ln}= coefficients of determination for linear resp. logarithmic results

Gauge	Andelfingen	Frauenfeld	Wängi	Halden	St. Gallen	Hundwil	Appenzell	Herisau	Jonschwil	Mosnang	Mogelsberg	Stein
river	Thur	Murg	Murg	Thur	Sitter	Urnä.	Sitter	Glatt	Thur	R.-bach	Necker	Thur
area [km²]	1700	212	78	1085	261	64	74	16.2	493	3.3	88	84
EV_{lin}	0.924	0.881	0.914	0.902	0.766	0.791	0.862	0.397	0.885	0.823	0.678	0.864
EV_{ln}	0.924	0.901	0.877	0.913	0.763	0.844	0.838	0.730	0.922	0.893	0.867	0.865
r^2_{lin}	0.922	0.828	0.906	0.901	0.764	0.791	0.861	0.396	0.884	0.821	0.678	0.860
r^2_{ln}	0.914	0.828	0.861	0.896	0.745	0.817	0.831	0.730	0.921	0.890	0.815	0.856

Table 11.1.2.2 Validation results for the Thur as explained variance coefficients EV_{lin} and coefficients of determination r^2_{lin}

	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	mean value
EV_{lin}	0.88	0.82	0.87	0.92	0.87	0.93	0.93	0.95	0.90	0.91	0.93	0.87	0.87	0.92	0.90	0.898
r^2_{lin}	0.88	0.82	0.86	0.92	0.87	0.92	0.93	0.95	0.90	0.90	0.93	0.86	0.86	0.91	0.89	0.893

measurements very well for the Thur basin as a whole. Snow melt induced floods as in January and February show some errors which can be explained by the sensitivity of melt to air temperature, in conjunction with errors in temperature interpolation. The flood events of August and September are simulated with high accuracy as well as the recession periods in February / March and October / November. The exact simulation of the November flood is especially remarkable because of its temporal position after a long low flow period. Accumulated errors in evapotranspiration calculation often leads to larger errors in such floods due to under/overestimation of soil moisture.

The peak flows of some flood events in the summer are simulated too small. Since these events are induced by convective thunderstorms it is reasonable to assume that the density of high temporal resolution rain gauges does not provide sufficient information on the spatial structure of these kinds of events. Table 11.1.2.1 summarises the results for the calibration period.

Following the calibration, the methods for modelling the components of the hydrological cycle and their parameters have not been changed. There are no parameters to calibrate for each of the seasons or for single years, while the characteristic intra-annual course of phenological development was also assumed to be identical in all years, varying only between different vegetation and with altitude. Validation was carried out by using all other available observed discharge data from 1981 to 1995. In table 11.1.2.2 the explained variance coefficients (EV_{lin}) and the coefficients of determination for the linear data (r^2_{lin}) are summarised for the years 1981 to 1995. Obviously the model performance or model accuracy is satisfactory. Values of r^2 may even exceed those of the calibration run, for example in 1988.

For the estimation of model accuracy, not only the determination coefficients and the explained variance may be used but also the balances of main water balance components - precipitation P, evapotranspiration ET and runoff R, which are linked by the water balance law:

$$P = ET + R + \Delta S \qquad (11.1.2.1)$$

where ΔS is the change in storage contents which is assumed to be zero for long time periods, with similar initial and final states (with respect to the soil moisture, snow storage and groundwater storage, e.g. at the beginning or end of a calendar year). In this study, the runoff R is the only variable in the equation (11.1.2.1) that can be compared with simulation results. Table 11.1.2.3 gives an overview of the main land surface water cycle components for the

Table 11.1.2.3 main water cycle components for the Thur basin for 1981 to 1995 as mean yearly values

	precipitation P	evapotranspiration *ET*	runoff R		
	interpolat. [mm]	simulated [mm]	simulated [mm]	observed [mm]	simulation error
entire Thur basin	1500	550	900	860	+4.7%
subbasin Murg	1290	580	710	580	+22%
subbasin Stein/Thur	1870	410	1460	1357	+7.6%

Thur basin. The subbasin of the Murg river (gauge Frauenfeld) is a subbasin typical for lower elevation zones (400...1200 m a.s.l.) whereas the subbasin of gauge Stein/Thur is an alpine to high alpine subbasin, characterised by long duration snow coverage and high precipitation.

The errors in simulated runoff are always positive and sometimes large. However, for the entire basin of the Thur, the error in discharge is within the inaccuracy of measurements, whereas for the other subbasins the error is obviously larger. This is very probably induced by uncertainties in the precipitation data. To meet the observed discharges, very high and therefore unrealistic simulated evapotranspiration values would be necessary (e.g. subbasin Murg: 710 mm real evapotranspiration would be necessary to simulate 580 mm (observed) discharge). There are also karst-hydrologic effects occur in the subbasin of the upper Thur at the Stein gauge, leading to leakage from the Thur basin.

11.1.2.2 Model runs with climate change scenarios

The scenarios were applied as follows: Firstly, the actual value of the interpolated variable was calculated within the interpolation routines of the hydrological model for each grid cell. The second step was the spatial and temporal interpolation of the scenario values to the actual date and location. For temporal interpolation, simple linear interpolation to the actual Julian day was used (assuming the scenarios are valid for the middle of each month) whereas for spatial interpolation a 'nearest neighbour' method was applied (the Thur basin is covered by four scenario cells, each of which around 30 km in longitude × 60 km in latitude). In a third step, the scenario values were added to (absolute changes) or multiplied (by relative changes + 1.0) by the actual interpolated value. Then further modelling was carried out, like in the calibration run. To be consistent with other project groups, no land use changes and no changes in plant physiological properties such as increased stomatal resistances, were applied. This method of linear scaling is a very simple and possibly inaccurate method because the frequencies of rain days may change in a future climate, as too may the rain intensities or the diurnal distributions of vapour, radiation and wind. However, this methodology was seen as acceptable for a scenario study.

11.1.2.3 Interpretation of selected scenario results

Following the scenario runs, the time series of all 8 scenarios and of the control run were statistically analysed for changes in flood frequencies, changes in drought frequencies and changes in average balances of the main water cycle components runoff *R* and evapotranspiration *ET*. Changes in flow duration curves were also calculated on a daily basis, and changes in intra-annual hydrologic regimes were calculated on a monthly basis. This section concentrates on the UKHI2050, CCC2050 and UKTR6675 scenarios (referring to the year 2050).

An initial overview of the changes in the water balance due to the impact of climate scenarios is summarised in table 11.1.2.4. The main land surface water cycle components are compared with the control run for all scenarios according to the 2040 – 2050 time slice. The mean annual precipitation is slightly increased for all scenario results. The evapotranspiration values show larger differences between the control run and the various scenario runs, with largest relative changes in the alpine parts

Table 11.1.2.4 Changes in mean water balance for the Thur basin due to climate change impacts; ΔP, ΔET, and ΔR are changes in precipitation, evapotranspiration and runoff, respectively, with regard to the control run results and for the 1981 to 1995 period

scenario	basin/subbasin	precipitation *P* [mm]	ΔP [%]	evapotranspiration *ET* [mm]	ΔET [%]	runoff *R* [mm]	ΔR [%]
control run	entire Thur basin	1494	–	537	–	957	–
	subbasin Murg	1309	–	559	–	750	–
	subbasin Stein/Thur	1987	–	397	–	1590	–
UKHI 2050	entire Thur basin	1492	+0.1	620	+15.5	873	–8.8
	subbasin Murg	1314	+0.4	636	+13.8	678	–9.6
	subbasin Stein/Thur	1981	–0.3	471	+18.6	1511	–5.0
UKTR 6675	entire Thur basin	1504	+0.7	626	+16.6	878	–8.3
	subbasin Murg	1327	+1.3	642	+14.8	685	–8.7
	subbasin Stein/Thur	1994	+0.4	478	+20.4	1516	–4.7
CCC 2050	entire Thur basin	1515	+1.4	553	+2.9	962	+0.5
	subbasin Murg	1331	+1.7	572	+2.3	759	+1.2
	subbasin Stein/Thur	2018	+1.6	404	+1.8	1614	+1.5

(UKHI and XCCC). The combination of slightly increased annual precipitation and largely increased annual evapotranspiration results in a decrease of runoff, which is in the order of up to 10% as compared to the control run. However, these mean annual values are total values, not differing between single months or seasons. It is remarkable that the UKTR 6675 scenario shows the largest changes in evapotranspiration but not the largest changes in runoff. Although the results from the XCCC scenario runs show only very small changes in mean annual precipitation, evaporation, and runoff, the latter decreases throughout the summer and increases in the winter season. The runoff sums for the UKHI2050 and UKTR6675 scenarios also do not show reduced runoff over the whole year but rather show a higher flow in winter and lower flow in summer.

This leads to an analysis distinguishing between seasons and months as well as between the lower and upper parts of the Thur basin. Figure 11.1.2.4 shows the monthly percentiles for daily discharges extracted from the duration curves (see Fig. 11.1.2.5) for (a) high discharge Q_{347d} or $Q_{95\%}$, (b) mean discharge Q_{183d} or $Q_{50\%}$ and (c) low discharge Q_{18d} or $Q_{5\%}$ (note different scales). Results from the UKHI2050, from the XCCC2050, and from the UKTR6675 runs are compared to the control run results.

Decreasing summer flows and increasing winter flows

Obviously, the tendency of decreasing summer flow appears in all three graphs. Due to i) less summer precipitation in all scenarios as compared to the control run and ii) larger evapotranspiration rates due to higher temperatures and higher wind speeds, the soil moisture decreases. Thus, the recharge to the saturated zone will become smaller with the effect of smaller baseflow ($Q_{5\%}$) as well as smaller average flow ($Q_{50\%}$). Reduced soil moisture also reduces the potential for flood generation and reduces peak flows. The described effects are particularly important in regions with relatively low precipitation and high evapotranspiration, such as the lower parts of the Thur basin. Therefore the changes in intra-annual regimes and in flow duration curves, both with regard to daily discharge sums, are most significant in these regions but minor in the upper parts such as the subbasin of the Stein gauge (average elevation 1450 m a.s.l.).

Flow duration curves as in figure 11.1.2.5 are not appropriate in showing changes in peak flow generation because of the time discretisation of 1 day. Such changes in regime can be estimated by statistical analysis of hourly discharges as changes in return periods for given thresholds or as changes in absolute values for

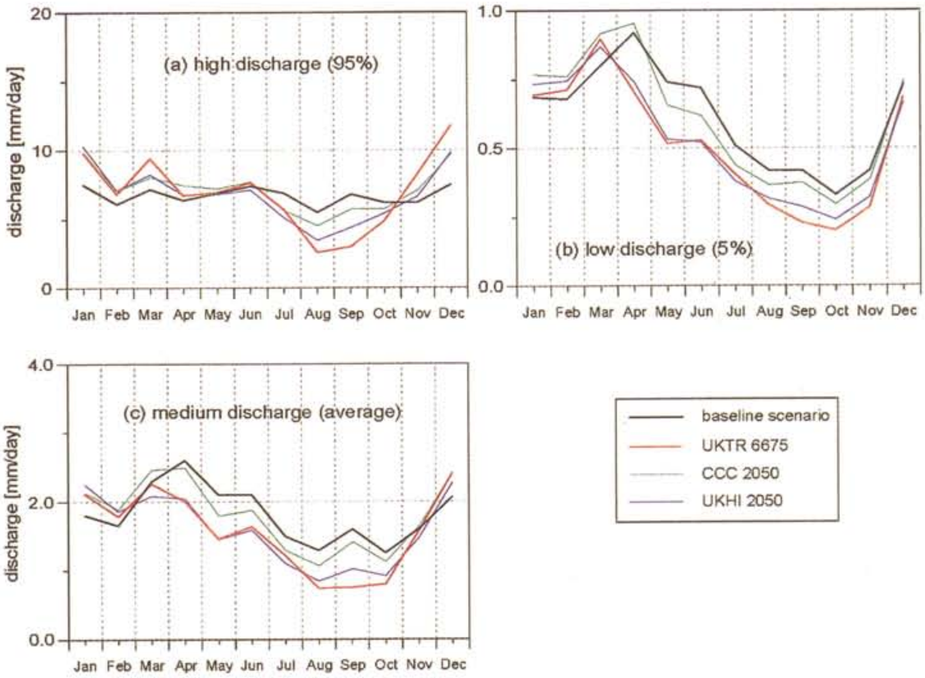


Figure 11.1.2.4 Hydrological regimes for various 2050 scenarios – daily discharges at the Andelfingen/Thur gauge (entire Thur); high discharge (95%): in 95% of time discharge is equal to or less than these values; low discharge (5%): discharge exceeds these values in 95% of time

given return periods. Both the peak flow statistics and the low flow statistics were carried out. Because of the non-linearity of the scenarios with respect to their seasonal course, the data sets for statistical analysis of peak flows were subdivided into summer and winter sets. A version without subdivisions was calculated as well (so-called yearly peak flows).

Risks caused by low flows are significantly lower than peak-flow risks. Thus, return periods of 2, 5, 10 and 20 years were considered for statistical low flow analysis. However, peak flow values are often needed for return periods of up to 1,000 years. As the model time in this study did not exceed 15 model years, the consideration of return periods longer than 50 years is not

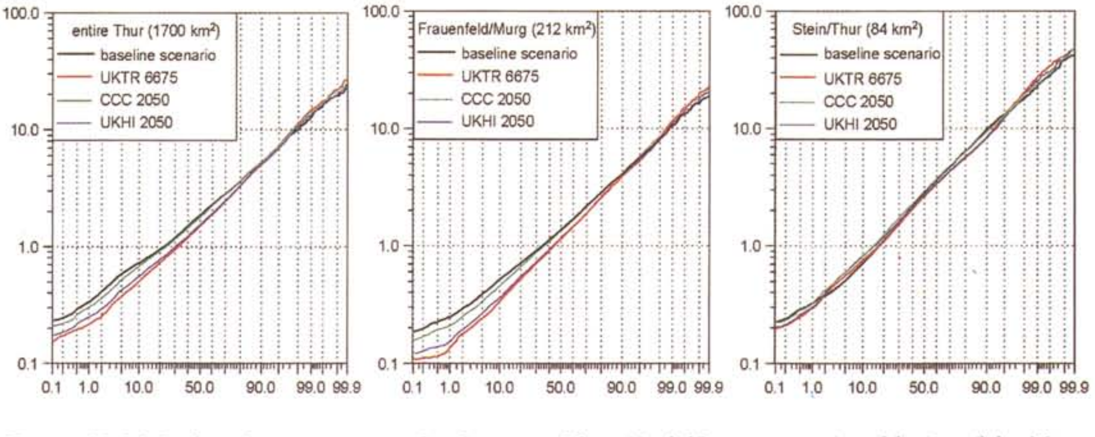


Figure 11.1.2.5 flow duration curves for the entire Thur (Andelfingen gauge), subbasin of the Murg (Frauenfeld gauge) and alpine subbasin of the Stein gauge (x-axis: duration as a percentage, y-axis discharge in mm/day)

justified. With regard to the high costs caused by 5 to 20 year floods, it may be important enough to indicate how floods with short return periods could change under changed climate conditions. While this is the case in a mountainous environment, populations in the downstream regions of the River Rhine are more endangered by floods with return periods of 50 up to 1,000 years. For these larger areas, daily discharges with a long term data basis can be used to facilitate flood flow estimations for longer return periods.

For the statistical analysis of peak flows, the probability distribution function for maxima after Gumbel (extremal distribution type 1) was used, whereas for the low flow analysis the extremal distribution of type 3 (according to Weibull, E III) was used (Dyck, 1980). For low flow analysis, the yearly minima of the 7-day moving average of the discharge (referred to as Qlow) were used, whereas for peak flow statistics the hourly maxima for the summer season (May to October, referred to as Qpeak,s) and the maxima for the winter season (November to April, referred to as Qpeak,w) were taken as separate data sets beside the yearly peak flows (Qpeak). Like in the analysis of the mean water balances and of flow duration curves, the analysis was focused on the entire Thur basin as well as on a typical alpine subbasin (Stein gauge on the upper Thur river) and a typical pre-alpine subbasin (Frauenfeld gauge on the Murg river). The results for the entire Thur basin are assumed to be representative for hydrological behaviour of the whole transition zone for the pre-alpine and alpine region of the northern Alps.

Figure 11.1.2.6 shows results of statistical analysis for peak flows and low flows in the entire Thur basin. Results from the control run are compared with results of UKHI 2050, CCC 2050 and UKTR 6675 scenario runs. Less summer precipitation in combination with higher evapotranspiration values causes decreasing soil moisture and less groundwater recharge, and thus decreased low flows (–9% to –37% for various scenarios). Low soil moisture values also

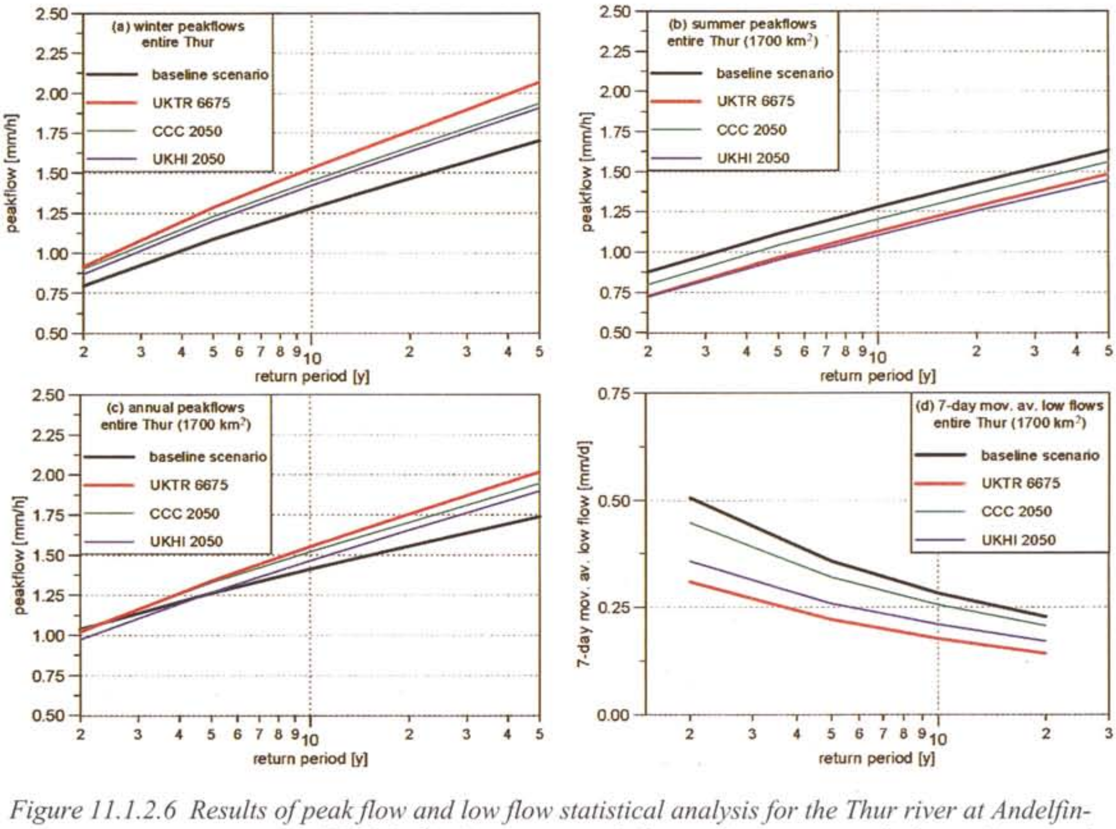


Figure 11.1.2.6 Results of peak flow and low flow statistical analysis for the Thur river at Andelfingen gauge (1700 km²); (a) winter peak flows, (b) summer peak flows, (c) annual peak flows, (d) low flows

affect the peak flow generation – consequently summer floods also decrease by 4% (CCC2050) to 11% (UKHI2050). On the other hand, higher winter precipitation in combination with a rising 0°C level will cause substantial rises in winter peak flows. For the entire Thur basin the 50-year winter flood will rise between 12% (UKHI2050) and 21% (UKTR6675). Annual peak flows are statistically mainly controlled by winter peak flows, therefore the annual peak flows with 50-year return period will rise by 9% (UKHI2050) to 16% (UKTR6675). For return periods shorter than 5 to 10 years, no significant changes in flood characteristics will occur. It is worth noting, that the calculated changes in flood distributions are within the uncertainty bands of 15% for the 2-year flood and of up to 30% for the 50-year flood. However, the decreases in low flows are significant for UKTR6675 and UKHI2050 scenarios. This seems to be one of the most important impacts of climatic change with a view to the changing availability of water resources for water supply, cooling and process water, inland navigation, irrigation, etc.

Similar results to those of the entire Thur basin are shown in figure 11.1.2.7 for the prealpine subbasin of the Murg river (Frauenfeld gauge, 212 km²). Contrasting trends for summer and winter peak flows are superposed to a quasi steady state in annual peak flows. Only the XCCC2050 results show an increase in annual peak flows of around 10% for all return periods, whereas these peak flows remain constant for the UKHI2050 scenario and peak flows from UKTR6675 scenario shift upwards by only 5%, compared to the control run. For the lower parts of the Thur basin, no scenario generates peak flow shifts that are dramatic enough to give reasons for new flood protection measures. On the other hand, as in the entire Thur basin, the low flow statistics indicate considerable smaller low flows following climatic changes.

The flood and low flow statistics for the alpine part show distinctive differences when compared with the lower regions or the entire Thur basin. However, the evapotranspiration is higher than in the control run, while the summer

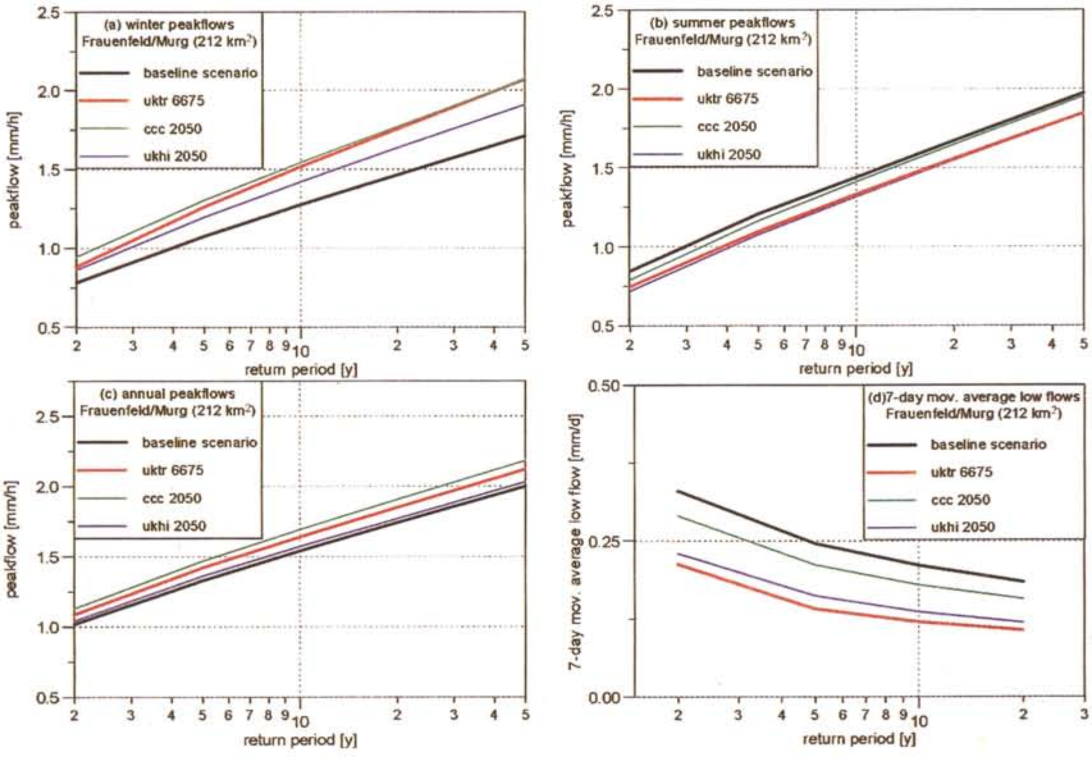


Figure 11.1.2.7 Results of peak flow and low flow statistical analysis for the Murg subbasin at Frauenfeld gauge (212 km²); (a) winter peak flows, (b) summer peak flows, (c) annual peak flows, (d) low flows

discharge also decreases. The absolute changes in evapotranspiration (between +7 mm for XCCC2050 and +81 mm for UKTR6675 scenarios) and thus the resulting runoff changes (–79 mm for UKHI2050 to +24 mm for XCCC2050) are small, when compared with absolute runoff values of the control run (1590 mm/y). The XCCC2050 results even indicate a rising annual discharge, whereas the other scenarios result in decreasing discharge. The minor effect of evapotranspiration on decreasing discharge when compared with lower regions is evident from figure 11.1.2.8 (b) and (d). Summer peak flows as well as droughts remain statistically constant with a slight tendency to decreasing peak flows for short return periods of up to 5 years and a very slight increase in low flows for short return periods, too. This may be an effect of variance in data and uncertainty in parameter estimation of the distribution function (only 15 years were analysed) and therefore the changes are not significant. More important and quite significant for the alpine regions (here valid below ≈ 2,300 m a.s.l. only) are the changes in winter peak flows due to higher winter precipitation in conjunction with a rising temperature (see figure 10.4.3), which is leading to a larger fraction of liquid precipitation and thus to less storage effects of snow cover.

Winter peak flows will increase by an average 53% compared with the control run (XCCC2050: +37%; UKHI2050: +52%; UKTR6675: +70%). Because the absolute winter peak flow values in the control run are less than the values of summer peak flows (in particular for short return periods), changes in winter peak flows due to climate scenarios only lead to significant changes in annual peak flows for return periods longer than 5 years. For the XCCC2050 scenario, the changes in annual peak flows are minor (max. +15%) and within the uncertainty bands, whereas changes for UKHI2050 (+26% for 50-year flood) and UKTR6675 scenarios (+42% for 50-year flood) exceed the uncertainty limits. Thus the effects of changes in flood regimes are important for the alpine subbasins, whereas the changes in low

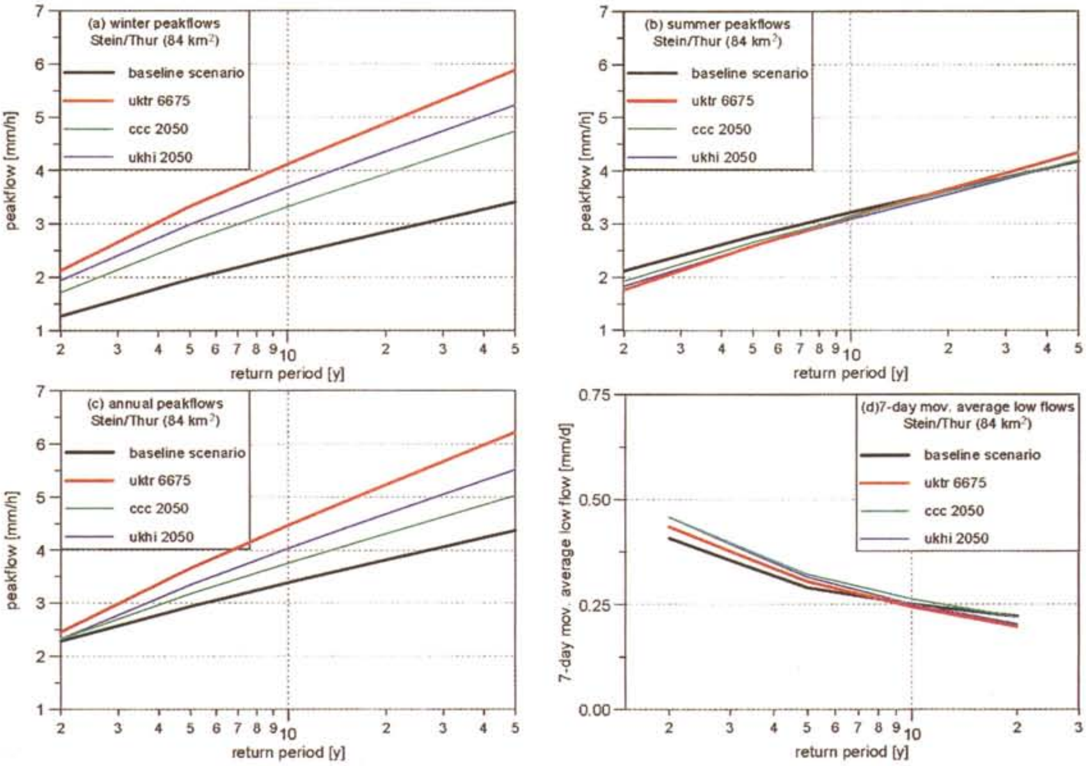


Figure 11.1.2.8 Results of peak flow and low flow statistical analysis for the alpine subbasin at the Stein gauge (84 km²); (a) winter peak flows, (b) summer peak flows, (c) annual peak flows, (d) low flows

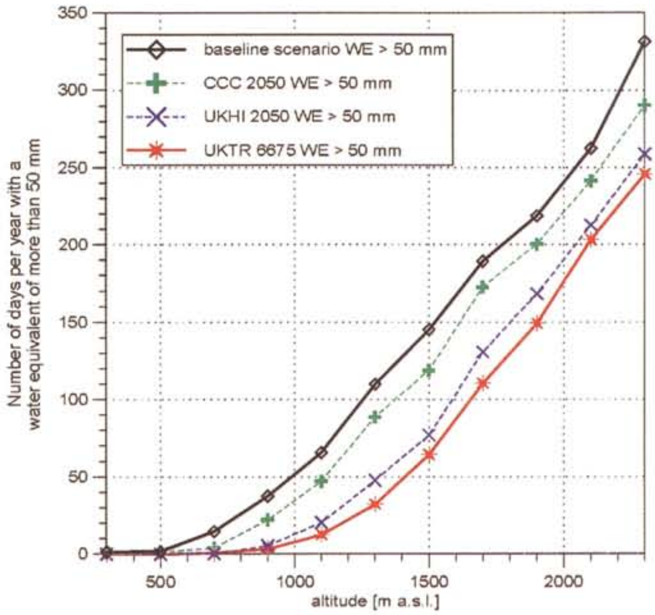


Figure 11.1.2.9 Altitude dependence of snow cover duration for a selected minimum snow water equivalent of 50 mm and its change under the various climate change scenarios

flows become more important as the fraction of lower altitudes increases. However, as recent history shows, changes in winter peak flows (induced by rain falling onto a melting snow cover) may be very important for the entire Rhine basin (e.g. floods in winter 1992 and 1993).

The changes in snow cover duration strongly depend on the mean temperature shift of the particular climate change scenario, but less strongly on absolute altitude. For a statistical analysis, it is useful to express the snow cover duration as the number of days exceeding a given level of snow water equivalent. Thus, an altitude dependent statistical analysis of the snow cover is possible on the basis of a relatively simple estimable value. Figure 11.1.2.9 shows these relations between the snow cover duration and the altitude for the 50 mm – water equivalent exceeding duration. The shifts between these graphs are representative for all other snow water equivalence values, too, ranging from 10 mm to 300 mm in the analysis. Basin parts below 1,000 m a.s.l. will probably never experience enough snowfall for a snow cover duration of longer than a month.

Besides affecting the alpine vegetation and the soils (erosion due to heavy rain), this will strongly affect the winter tourism possibilities. Winter tourism will only be possible at a profitable duration above 1,500 m a.s.l. The negative shift in snow cover duration is smallest for the XCCC2050 scenario (minus 20 to 30 days), the scenario with the smallest temperature changes, and largest for the UKTR6675 – scenario (60 to 80 days), the scenario with the largest temperature changes.

11.1.3 Sauer and Saar catchments

11.1.3.1 Model calibration and validation

The hydrological model was applied to the catchments of the Prüm and Blies Rivers, situated in the Sauer and Saar basins, respectively. For the Prüm, a daily time series covering the period from 1975 to 1984, and for the Blies the period from 1962 to 1989 was used for all model and scenario runs. Both periods are within the period of 1961-1990 which was used for the baseline climate and the generation of the scenarios.

Different time periods were selected for calibration and validation purposes. Following the calibration process, the model was applied to the validation time series without changing any parameters. As an objective function, the frequently used NASH-SUTCLIFFE criterion of model efficiency (Nash and Sutcliffe, 1970) as a measure of the explained variance related to the observed discharge was used. The results

Table 11.1.3.1.1 Calibration and validation results for the Prüm, the Blies and subcatchments within the Blies basin, model efficiency expressed as explained variance percentage

Gauge	Prümzurlay	Hornbach	Althornbach	Contwig	Einöd	Neunkirchen	Reinheim
Basin	Sauer	Saar/Blies	Saar/Blies	Saar/Blies	Saar/Blies	Saar/Blies	Saar/Blies
River	Prüm	Hornbach	Hornbach	Schwarzbach	Schwarzbach	Blies	Blies
Area[km²]	574	94	424	529	1152	318	1798
Model eff. Calibration [%]	72	75	85	76	78	83	82
Model eff. Validation [%]	68	68	83	70	83	88	85

Table 11.1.3.2.1 Results for the Prüm river with respect to the 1975-1984 period according to the reference situation (control run) and the XCCC2050, UKHI2050, and UKTR6675 climate scenarios

Month	**Control Run**		**CCC2050**		**UKHI2050**		**UKTR6675**	
	Q[mm]	AE[mm]	Q[mm]	AE[mm]	Q[mm]	AE[mm]	Q[mm]	AE[mm]
January	76	3	83	7	78	18	75	10
February	70	4	68	7	63	14	66	7
March	65	15	61	21	56	28	62	24
April	45	34	45	40	43	45	39	39
May	33	61	32	65	31	69	31	63
June	23	72	22	75	21	76	21	77
July	26	78	23	82	23	83	24	80
August	16	64	14	67	13	72	11	77
September	16	43	13	47	11	50	8	53
October	28	21	23	26	21	29	18	25
November	41	8	37	13	30	14	41	11
December	73	3	76	9	66	17	67	15
Annual	512	406	497	459	456	515	463	481
Q winter[mm]	370		370		337		350	
Q summer[mm]	142		127		119		113	
Min7day[m;/s]	0.19		0.11		0.08		0.05	
Max daily[m;/s]	124		118		114		114	
Q5[m;/s]	30.7		29		27.2		27.2	
Q95[m;/s]	0.86		0.60		0.39		0.31	
N5[days]	183		155		136		141	
N95[days]	182		288		396		407	

Q – runoff
AE – actual evaporation
Q winter – November to April runoff
Q summer – May to October runoff
Min7day – minimum 7-day flow
Max daily – maximum daily flow
Q5 / Q95 – daily flow exceeding 5% / lower than 95%
N5 / N95 – number of days with flow exceeding Q5 / lower than Q95

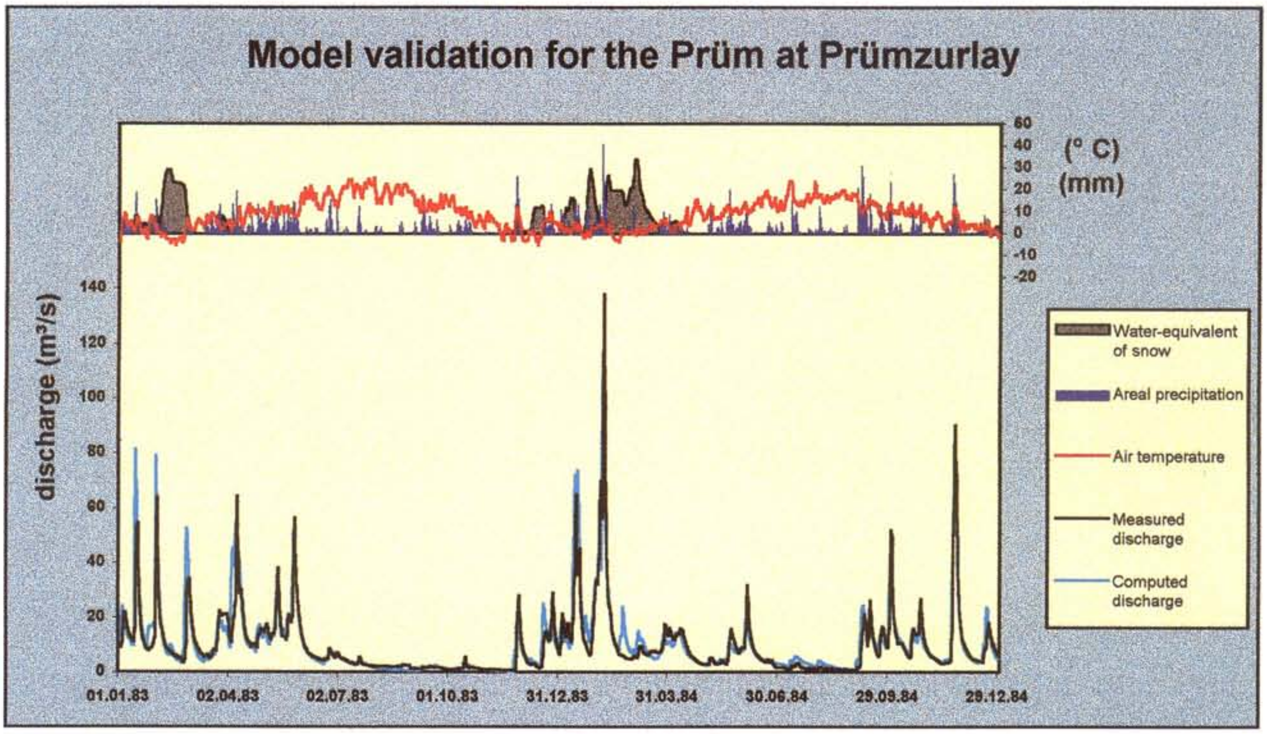


Figure 11.1.3.1.1 Results of the validation run for the Prüm river at Prümzurlay gauge (1983-1984)

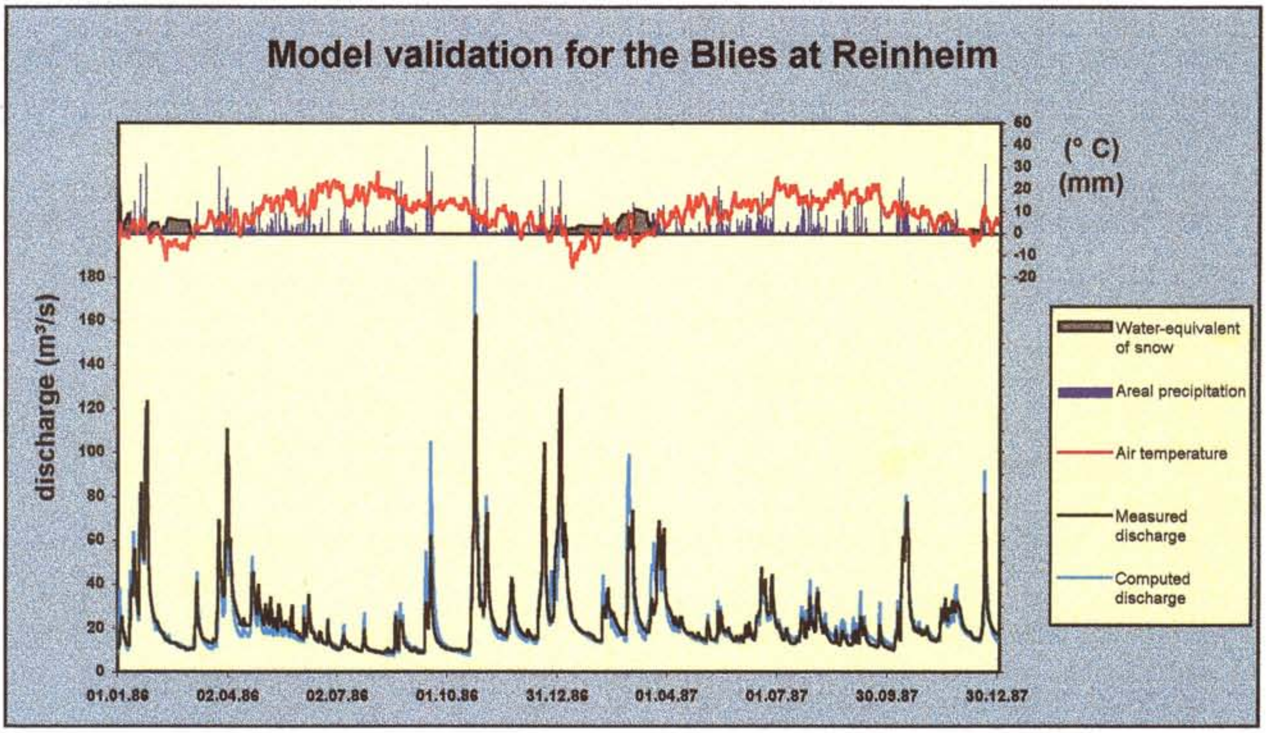


Figure 11.1.3.1.2 Results of the validation run for the Blies river at Reinheim gauge (1986-1987)

Table 11.1.3.2.2 Results for the Blies river with respect to the 1962-1989 period according to the reference situation (control run) and the XCCC2050, UKHI2050, and UKTR6675 climate scenarios

Month	**Control Run**		**CCC2050**		**UKHI2050**		**UKTR6675**	
	Q[mm]	AE[mm]	Q[mm]	AE[mm]	Q[mm]	AE[mm]	Q[mm]	AE[mm]
January	42	13	43	18	42	21	46	21
February	42	18	41	33	37	60	43	40
March	37	45	36	53	31	64	39	54
April	30	67	31	66	28	68	32	68
May	28	81	29	78	27	77	29	76
June	22	80	22	77	21	76	22	75
July	21	78	20	75	19	75	21	77
August	19	69	18	67	17	65	17	64
September	18	53	17	51	15	51	14	51
October	22	35	21	35	21	36	19	37
November	26	21	25	24	22	26	27	25
December	42	13	42	20	38	22	46	22
Annual	349	573	345	597	318	641	355	610
Q winter[mm]	220		218		199		233	
Q summer[mm]	129		127		119		122	
Min7day[m;/s]	19.8		22.9		19.8		22.0	
Max daily[m;/s]	361		390		331		374	
Q5[m;/s]	56.0		50.2		44.7		54.8	
Q95[m;/s]	5.81		6.19		5.31		5.66	
N5[days]	511		401		310		485	
N95[days]	510		434		666		549	

Q – runoff
AE – actual evaporation
Q winter – November to April runoff
Q summer – May to October runoff
Min7day – minimum 7-day flow
Max daily – maximum daily flow
Q5 / Q95 – daily flow exceeding 5% / lower than 95%
N5 / N95 – number of days with flow exceeding Q5 / lower than Q95

have been summarised in table 11.1.3.1.1. For the Prüm, the period 1975-1980 was used for calibration, and 1981-1984 for validation. Within the Blies basin, the 1972-1982 and 1983-1989 periods were used, respectively.

The results for the Prüm are not as satisfying as for the Blies basin. This is mainly caused by simulation errors during periods where the form of precipitation changes between rain and snow, which can be seen in figure 11.1.3.1.1. Besides model errors it may explained by the fact that there are only three recording meteorological stations within this topographically and climatologically highly differentiated catchment. Therefore local effects may not be well represented.

The results for the Blies basin are significantly better. At some gauges the results for validation are even better than for calibration. Figure 11.1.3.1.2. shows the validation for the years 1996 and 1987. Although snow conditions do also occur, the model performs quite well and leads to the conclusion that the snow model component is not too bad. However, the modelling of snow is still a problematic task also in other catchments.

11.1.3.2 Model runs with climate change scenarios

Following the calibration and validation process, the model was re-run with all climate

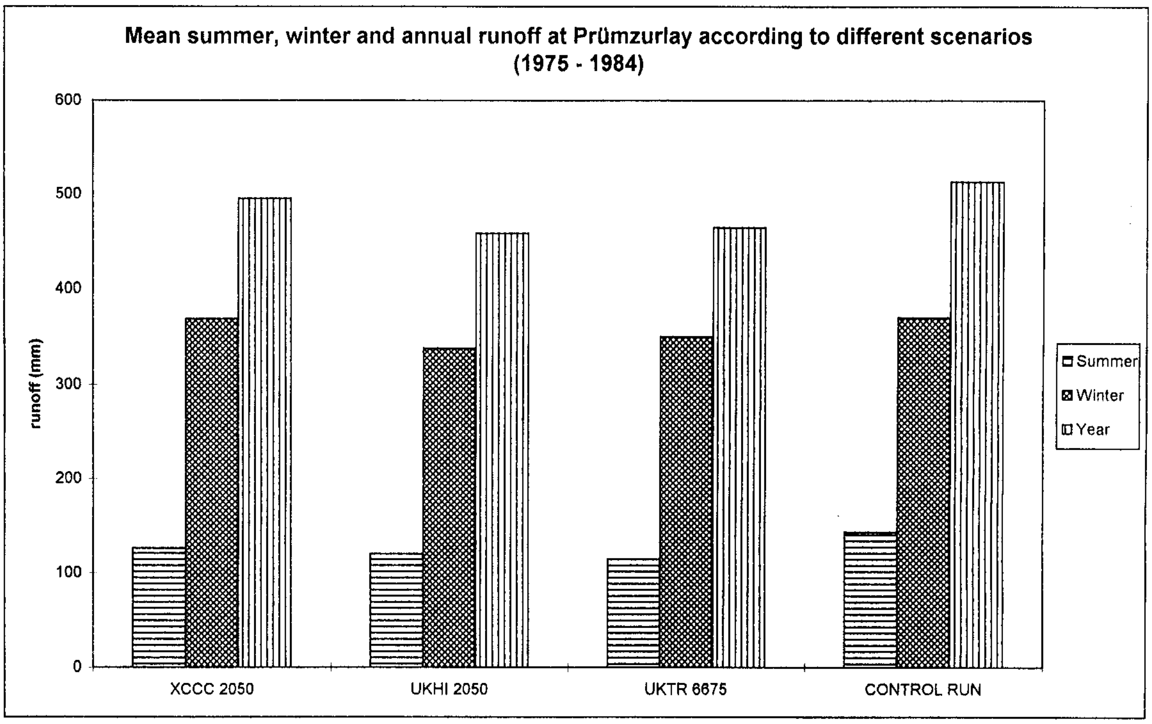


Figure 11.1.3.2.1 Mean summer, winter and annual runoff for the Prüm up to Prümzurlay according to different scenarios

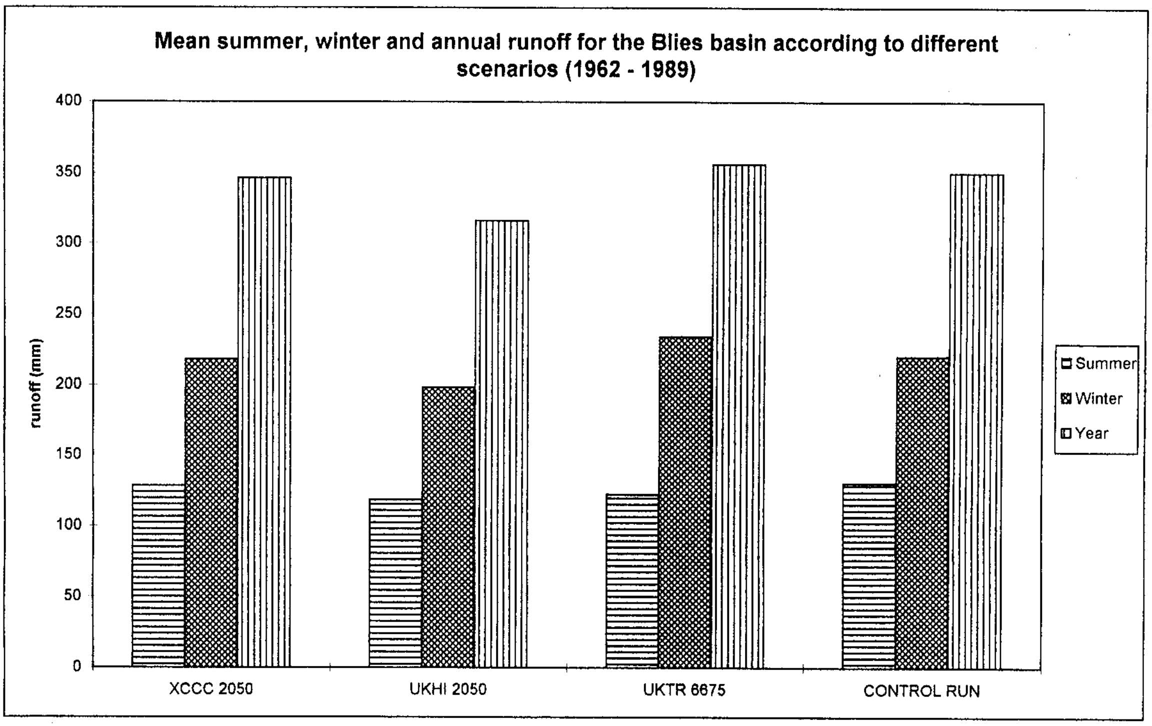


Figure 11.1.3.2.2 Mean summer, winter and annual runoff for the Blies basin according to different scenarios

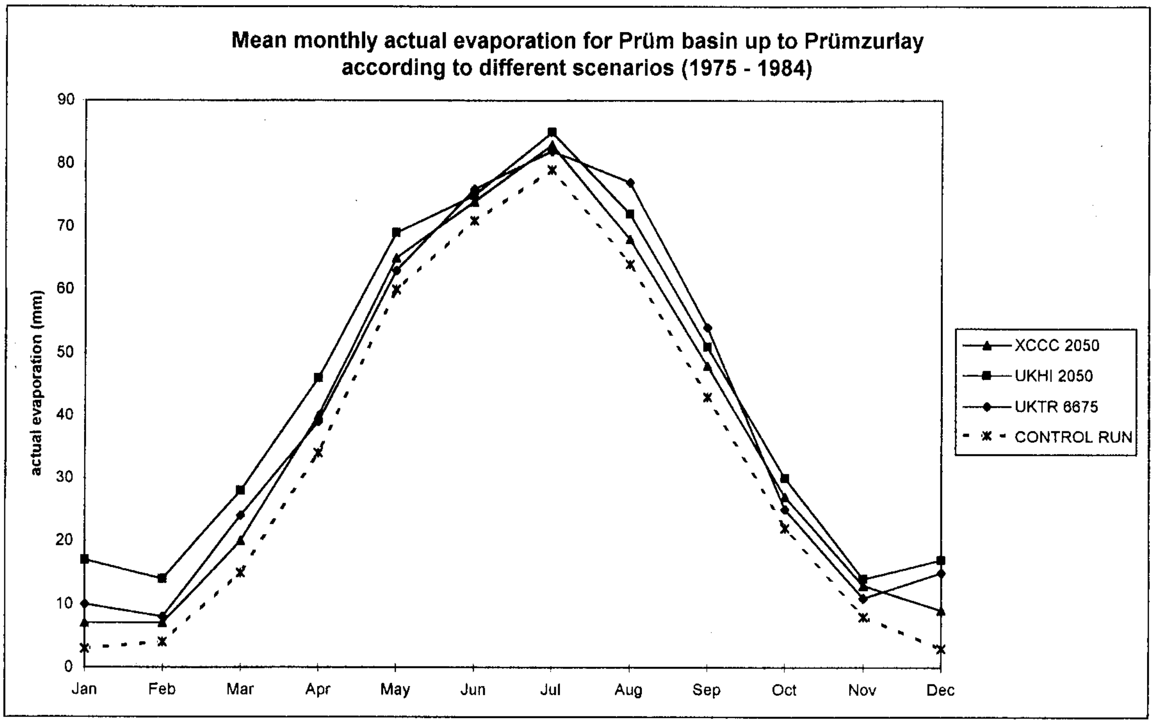


Figure 11.1.3.2.3 Mean monthly actual evaporation for the Prüm up to Prümzurlay according to different scenarios

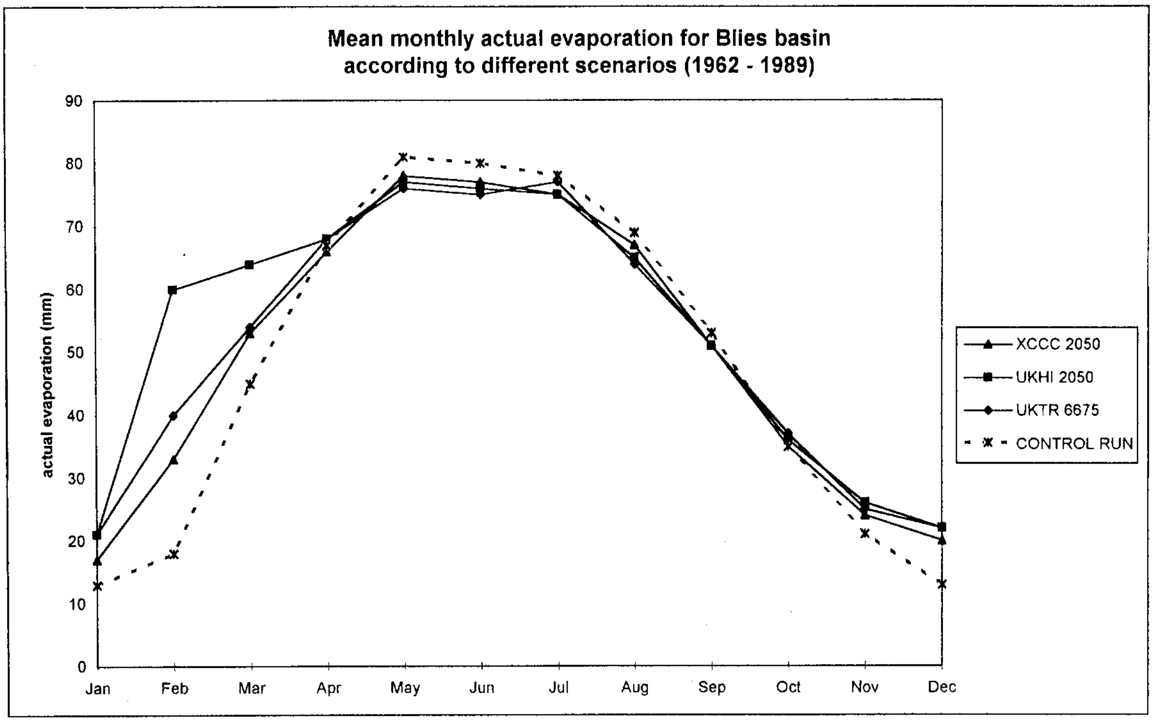


Figure 11.1.3.2.4 Mean monthly actual evaporation for the Blies basin according to different scenarios

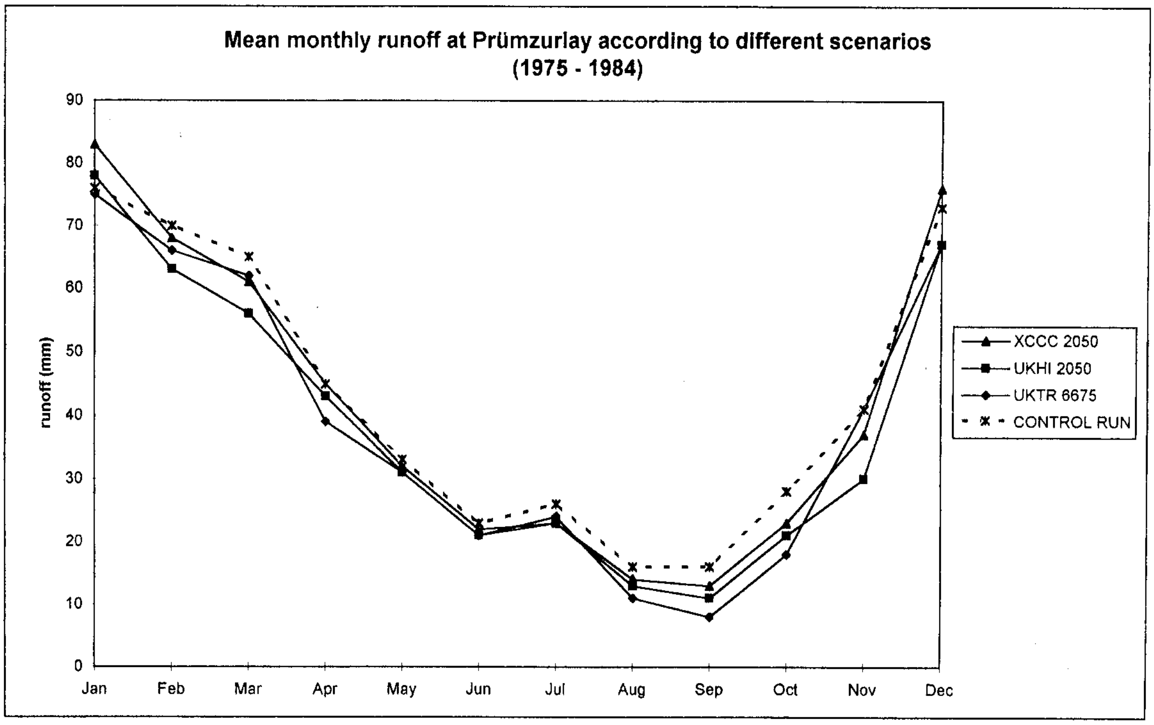


Figure 11.1.3.2.5 Mean monthly runoff for the Prüm up to Prümzurlay according to different scenarios

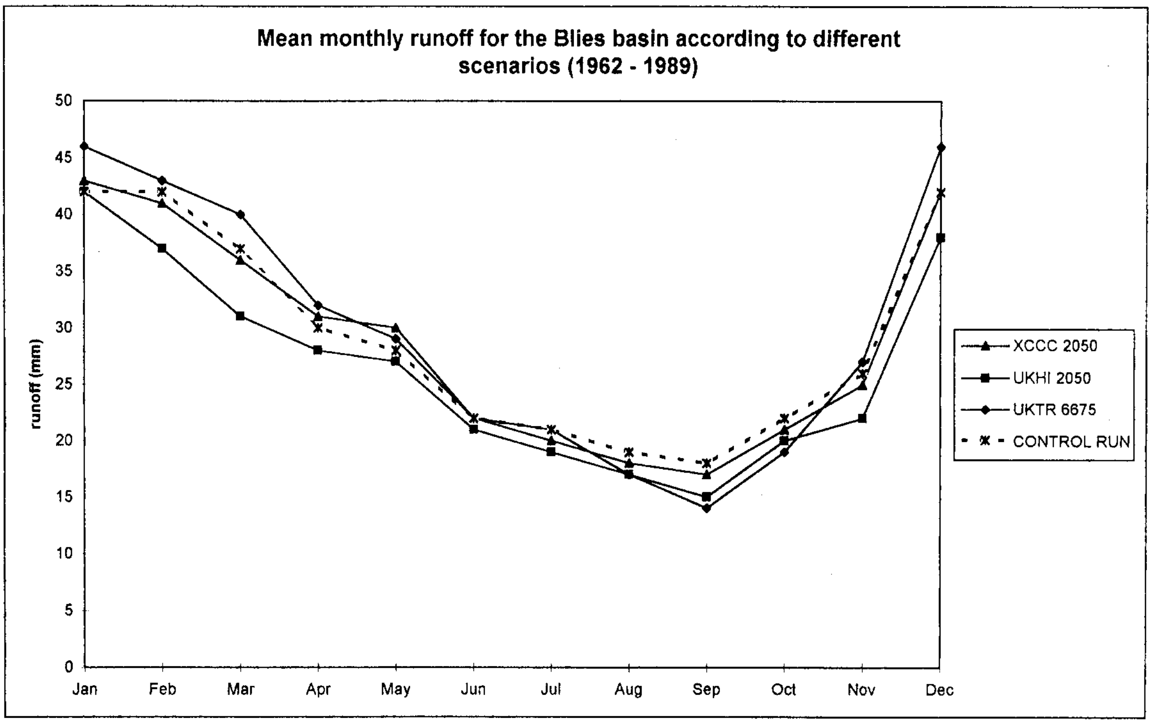


Figure 11.1.3.2.6 Mean monthly runoff for the Blies basin according to different scenarios

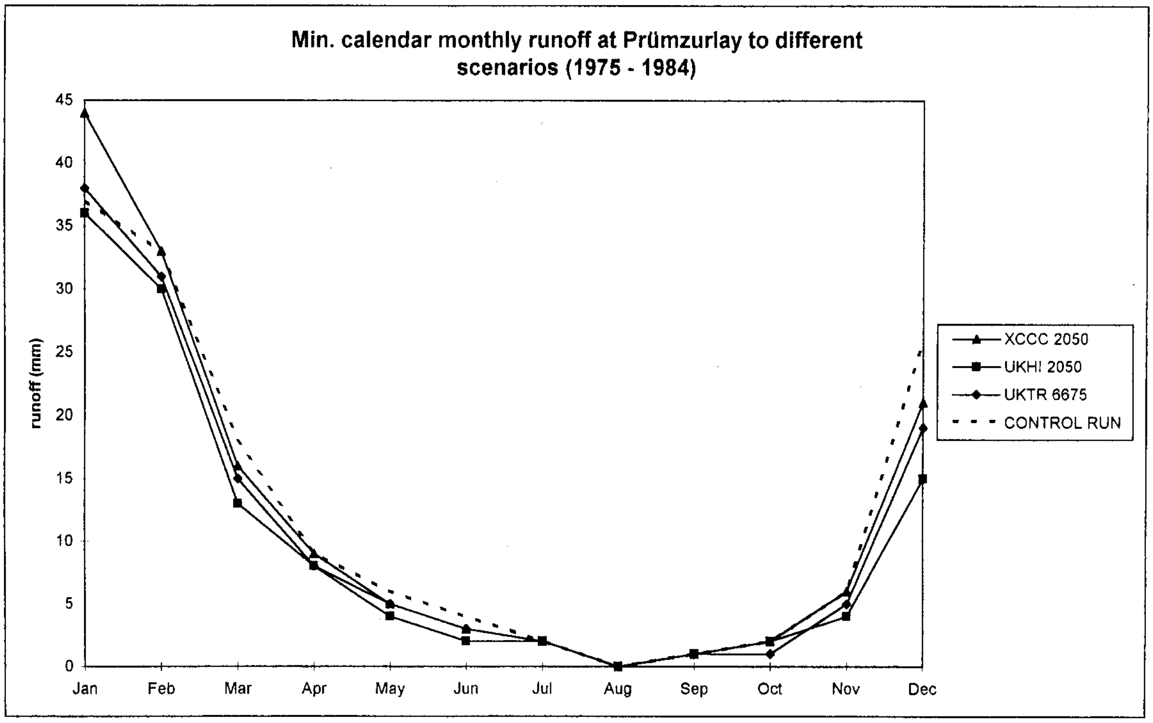


Figure 11.1.3.2.7 Minimum calendar monthly runoff for the Prüm up to Prümzurlay according to different scenarios

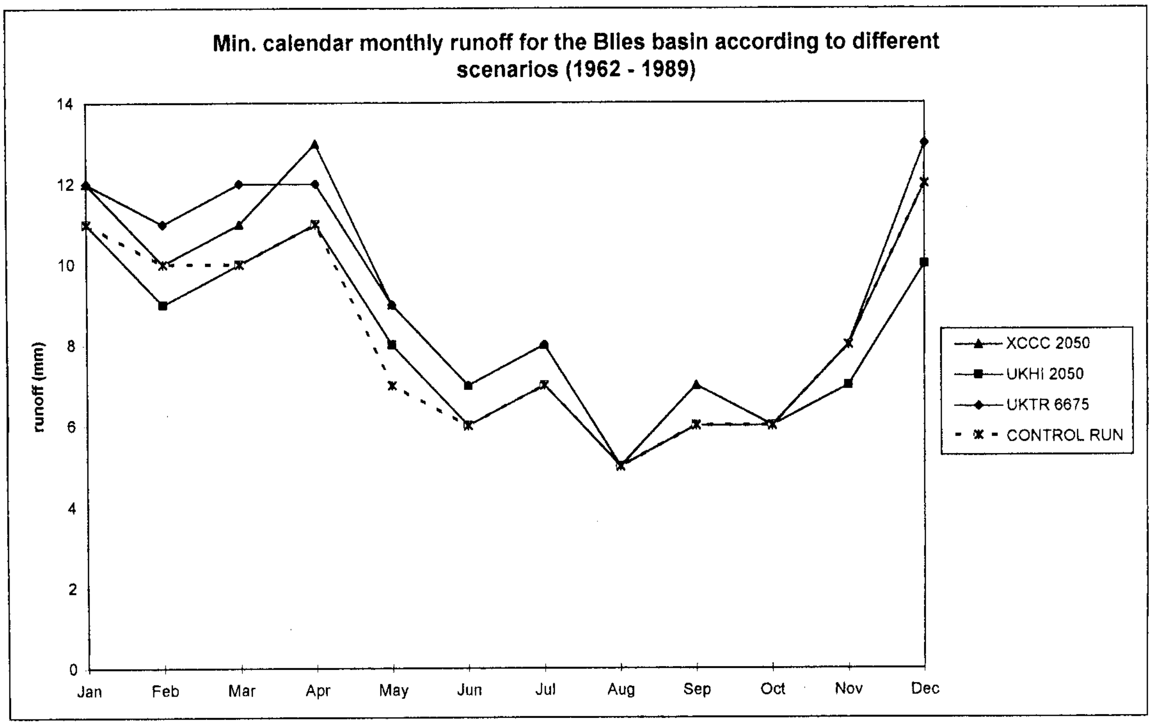


Figure 11.1.3.2.8 Minimum calendar monthly runoff for the Blies basin according to different scenarios

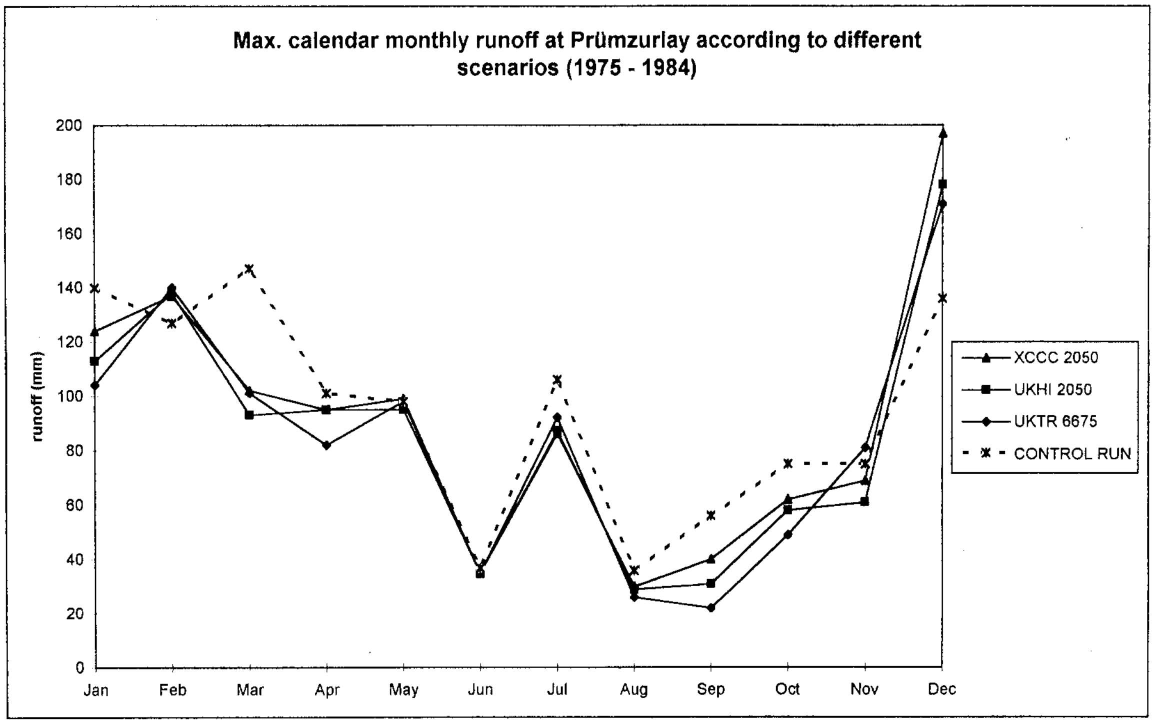


Figure 11.1.3.2.9 Maximum calendar monthly runoff for the Prüm up to Prümzurlay according to different scenarios

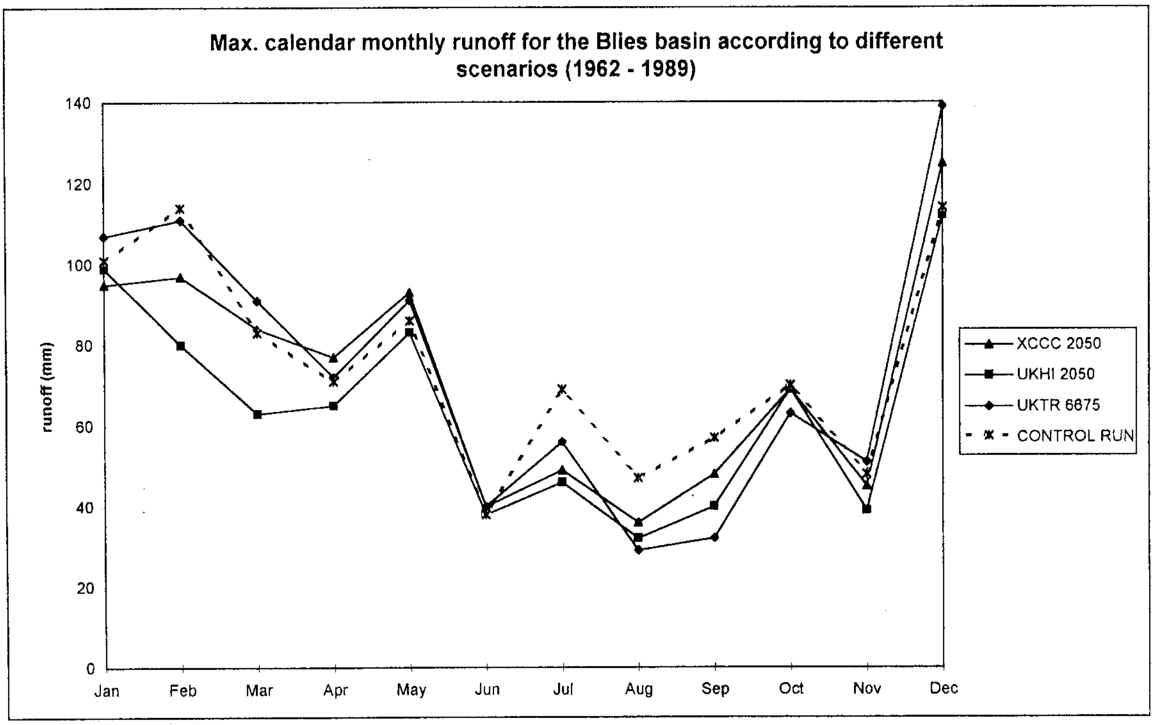


Figure 11.1.3.2.10 Maximum calendar monthly runoff for the Blies basin according to different scenarios

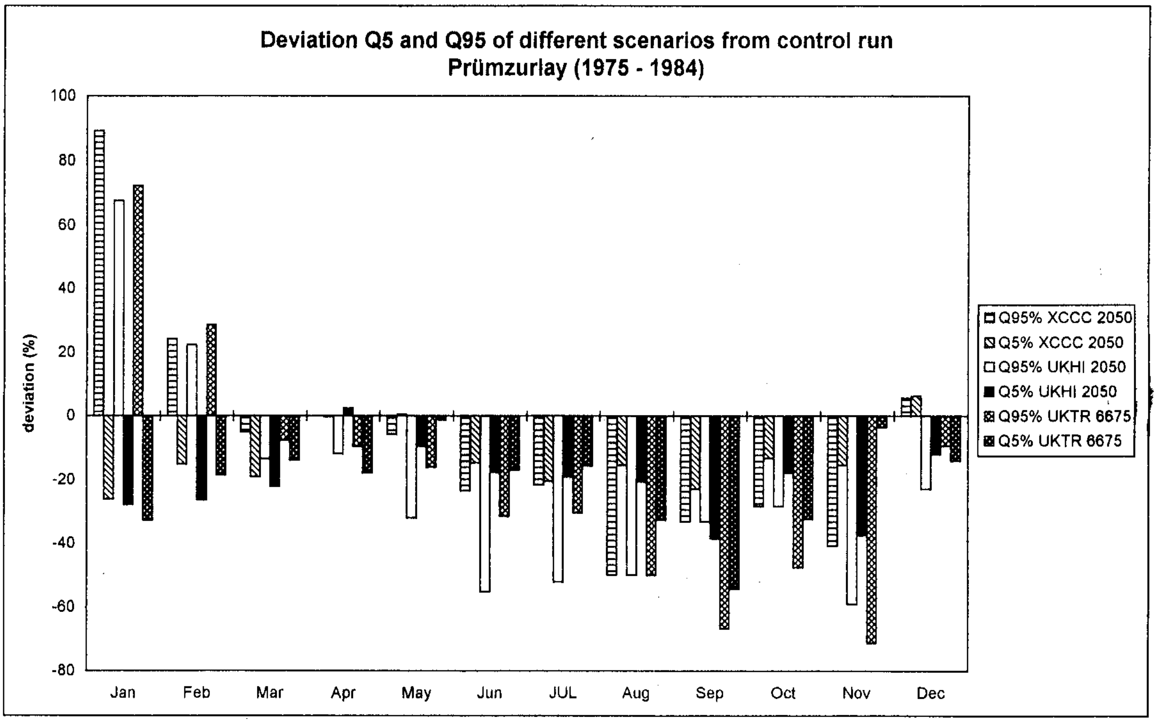


Figure 11.1.3.2.11 *Deviation of mean monthly Q5 (daily flow exceeding 5%) and mean monthly Q95 (daily flow lower than 95%) of different scenario runs from control run for the Prüm river up to Prümzurlay*

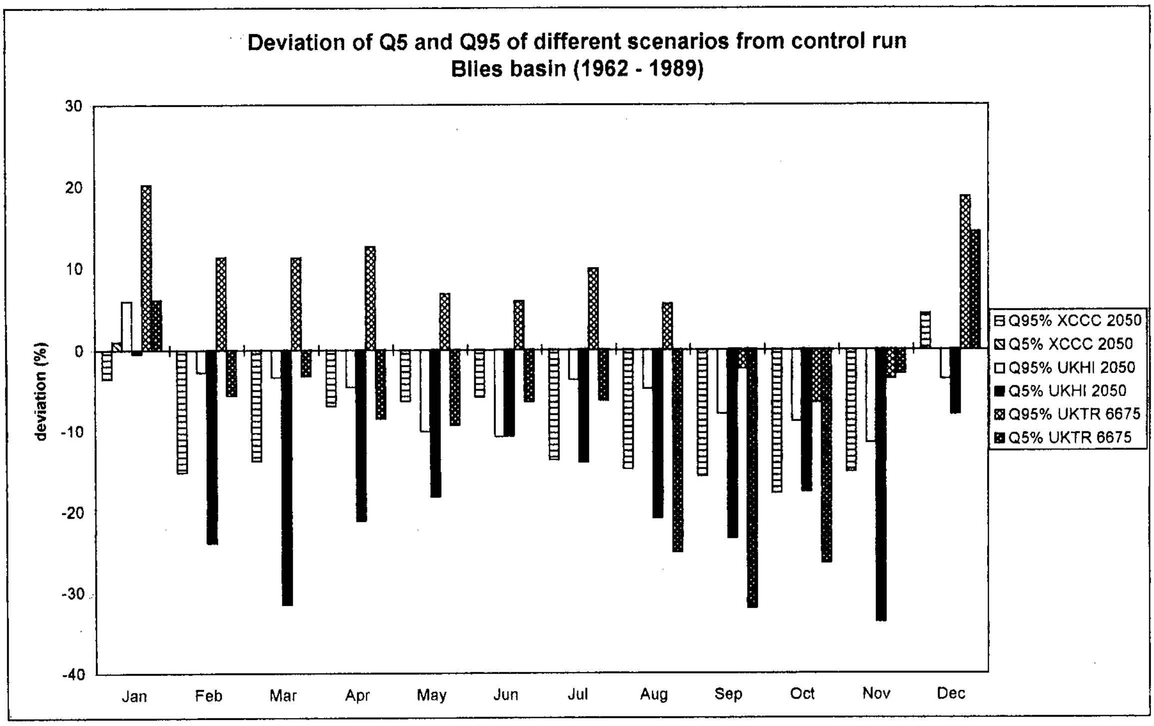


Figure 11.1.3.2.12 *Deviation of mean monthly Q5 (daily flow exceeding 5%) and mean monthly Q95 (daily flow lower than 95%) of different scenarios from control run for the Blies basin*

change scenarios. Changes in all provided meteorological variables have been applied to the recorded meteorological data. To allow for comparison with other project groups, no changes in land use nor plant physiological characteristics have been taken into account. Additionally, there is no common scientific agreement on what will happen to the plants due to an increase in CO_2 and rise in air temperature. The results for the Prüm and the Blies are given in table 11.1.3.2.1 and 11.1.3.2.2 and figure 11.1.3.2.1 to 11.1.3.2.12.

11.1.3.3 Interpretation of selected scenario results

Interpretation of the scenarios refers to the tables and figures of chapters 10.5 and 11.1.3.2 and is not explicitly mentioned during the following explanations.

The XCCC2050 scenario

As a result of the CCC2050 scenario, only minor changes in hydrological characteristics are indicated. At the Prüm, the rise in actual annual evaporation overcompensates for the precipitation increase and is uniformly distributed over the year. Precipitation will increase in winter and decrease during summer. Therefore, annual runoff decreases by 3 percent mainly during the summer half year, especially from September to November. The maximum calendar runoff is slightly decreased, and minimum calendar 7-day flow decreases significantly. This corresponds to the number of days with flows exceeding Q5 (N5) and lower than Q95 (N95), respectively. Extended low flow periods are indicated whereas high flows are reduced.

At the Blies the changes are similar but even less. Annual as well as mean monthly runoff are not affected, increases in annual precipitation and evaporation are of the same magnitude and therefore have no effect. The maximum daily flow increases by 8 percent but the number of days exceeding Q5 decreases. Also the number of days lower than Q95 is reduced, indicating that both high and low flow periods will be shortened.

The UKHI2050 scenario

The scenario results are mainly characterised by a strong increase in actual annual evaporation of about 70 mm at the Blies and 110 mm at the Prüm due to a high temperature rise, especially in January and February. The seasonal changes are different. For the Prüm area, actual evaporation shows an increase all over the year more pronounced during winter than in summer. For the Blies an increase can only be noted during the winter half year with extremely high rises in February and March. Within the summer half year evaporation is indicated to decrease slightly. A rise in the annual precipitation amount is overcompensated by the changes in actual evaporation. The seasonal distribution of precipitation will be affected, showing a minor reduction in summer and larger rise in winter. Annual runoff becomes reduced by 10 percent, affecting both summer and winter runoff. With the exception of January, runoff decreases throughout the year, particularly in extended low water periods from August to October. The number of days with flows lower than Q95 will be extended clearly. Maximum daily flow is reduced, as is the number of days with flows exceeding Q5.

The UKTR6675 scenario

Annual actual evaporation indicated by the transient scenario will increase in both study areas. The rise of 75 mm according to the Prüm catchment is twice as much as indicated for the Blies catchment. For the latter area evaporation increases only in winter and is slightly reduced during summer. The increase in precipitation amount is of the same magnitude, so that the annual runoff is not mainly affected within the Blies basin. Due to the contrary trend in precipitation changes, outlining an increase during winter and a decrease in summer, runoff will shift correspondingly. According to the flows exceeding Q5 and falling below of Q95, no major changes can be expected.

For the Prüm a rise in evaporation can be noted every month. The changes are higher in the winter season than in summer. Within this area the changes in precipitation follow the same pattern as stated before. The annual rise is only 25 mm and is therefore significantly lower than the rise in evaporation. This leads to a slight decrease in annual runoff amount but clearly affects the end of summer and the autumn. Correspondingly, low water periods are extended significantly. Though the number of days with flows exceeding Q5 is reduced, no major changes are made to the maximum daily flow.

11.1.4 Overijsselsche Vecht catchment

11.1.4.1 Model calibration and validation

Hydrological component

The hydrological component of the lowland model was extensively tested for the subcatchment of the Radewijkerbeek, which covers an area of 113 km^2 within the central part of the Vecht catchment (Parmet and Raak, 1995). Combination of land use, soil-physical and seepage data resulted in 157 hydrological units, for which simulations were carried out, using the MUST model. Computed actual evapotranspiration was indirectly validated using observed groundwater levels, and was subsequently used as input for the rainfall-runoff model. The Wageningen Model was calibrated using observed discharge data for the March 1980 to June 1983 period. Computations were carried out using the sealed ('paved') area module, based on the number of inhabitants and an estimated daily water consumption of 200 l per inhabitant, including industrial water use. The model efficiency was used as an optimisation criterion (Nash et al., 1970), which describes the percentage of initial variance of observed discharge data that is explained by the model. Table 11.1.4.1 shows the annual average values of the water balance components, and the model efficiencies for the 1980 – 1985 calibration period. The table shows good results on an annual basis including the model efficiency of the discharge computation. The residual terms of the water balance are also small.

Flow routing component

Calibration of the flow routing component with the Muskingum method was based on the determination of the travel time (K) for a certain river reach. The travel time was derived from observed daily discharge data. Since for some river reaches the time of travel is less than one day, the time step of the computed daily discharge data was reduced to six hours by linear interpolation. The flow routing procedure was split into two steps. In the first step, the discharges of the German subcatchments were routed to the German-Dutch border near Emlichheim gauging station. In the second step, the discharges from Emlichheim and those of the Dutch subcatchments were routed to the mouth of the Vecht catchment, near Vechterweerd gauging station. Table 11.1.4.2 gives the travel times from different subcatchments.

Validation

Validation of the model was carried out in two steps. Firstly, the hydrological component was validated for the subcatchments. For the subcatchments in the German part of the Vecht catchment, the available discharge data allowed for validation for a period of at least seven years

Table 11.1.4.1 Annual values of the water balance, i.e. precipitation (P), evapotranspiration (E), net seepage (SP), recorded discharge (Q_{rec}), computed discharge unpaved (Q_{unpav}), paved (Q_{pav}) and total (Q_{com}) and closing terms (d) (in mm), and model efficiency (R) (in %) for the Radewijkerbeek subcatchment for the period 1980-1985

Year	P	E	SP	Q_{rec}	d_{rec}	Q_{unpav} [1]	Q_{pav} [2]	Q_{com} [1]+[2]	d_{com}	R
1980	763	484	7	271	15	280	19	299	–13	72
1981	895	484	7	379	39	391	20	411	8	88
1982	649	523	7	237	–104	209	18	227	–93	86
1983	830	558	7	299	–20	268	19	287	–8	85
1984	891	474	7	370	54	371	20	391	33	89
1985	751	506	7	298	–46	260	18	278	–26	65
Avg 80-85	797	505	7	309	–10	297	19	316	–17	84

Table 11.1.4.2 Travel times (factor K for the Muskingum method), for the German subcatchments upstream of Emlichheim (left), and for the Netherlands subcatchments until Vechterweerd (right)

Subcatchment	Travel time (hours)	Subcatchment	Travel time (hours)
Vecht-Bilk	34	Emlichheim	42
Steinfurter Aa	34	Afwateringskanaal	33
Dinkel-South	32	Radewijkerbeek	28
Dinkel-North	16	Almelo-de Haandrik	24
Vecht-Neuenhaus	16	Ommerkanaal	15
Lee	8	Regge	14
Vecht-Germany	0	Vecht-Netherlands	0

Table 11.1.4.3 Percentiles of daily observed and computed discharge for Emlichheim station (German part Vecht catchment) for the 1980-1989 period and Vechterweerd station (whole Vecht catchment) for the 1980-1983 period (in m^3/s)

Station	Discharge	5%	25%	50%	75%	95%	max
Emlichheim	Observed	2.7	6.4	12.7	25.2	65.6	210.0
	Computed	1.0	4.9	13.7	24.8	59.4	174.6
Vechterweerd	Observed	5.3	9.2	24.2	47.5	114.4	311.0
	Computed	3.1	8.8	28.6	54.1	111.3	314.3

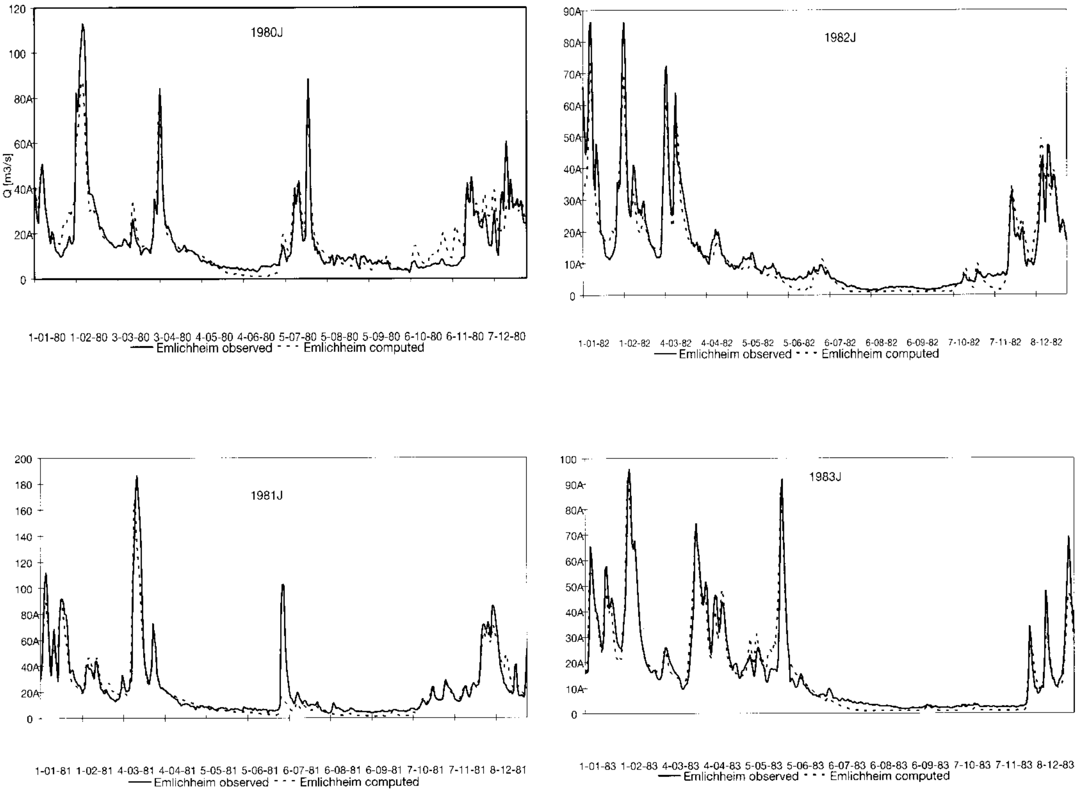


Figure 11.1.4.1. Observed and computed daily discharge For Emlichheim (German part Vecht catchment) for the years 1980-1983 (in m^3/s)

Table 11.1.4.4 Average values of precipitation (P), evapotranspiration (E), seepage (SP), observed and computed discharge (Q_{obs}, Q_{com}), closing terms of the water balance (d_{obs}, d_{com}), (in mm/year) and the average model efficiency (R), (in %) for Emlichheim station for the 1980-1989 period and Vechterweerd station for the 1980-1983 period

Station	P	E	SP	Qobs	dobs	Qcom	dcom	R
Emlichheim	813	487	−1.5	354	−29	338	−13	87%
Vechterweerd	786	513	0	299	−27	315	−42	90%

in all cases but one. For the Netherlands' part, validation was only possible for the Radewijkerbeek subcatchment. In general the water balance was simulated well, with low residual terms. Average model efficiency, as far as could be determined from observed discharges, varied between 86 and 70%. In view of the model performance for the German subcatchments and the Radewijkerbeek subcatchment, it was assumed that a similar performance was achieved for the other subcatchments in the Netherlands as well.

Secondly, the performance of the entire lowland model, including both the hydrological component and the flow routing, was validated against data of the Emlichheim gauging station (German part) for the 1980-1989 period, and Vechterweerd (whole catchment) for the period 1980-1983. Figures 11.1.4.1 and 11.1.4.2 give the observed and computed hydrographs for the years 1980 – 1983. Table 11.1.4.3 gives the percentiles of observed and computed discharge. The figures show a good fit, which is also reflected by the high model efficiencies (table 11.1.4.4). However, for Emlichheim, both low and peak-flows are underestimated (cf. table 11.1.4.3). The underestimation of the low flows may be due to the simple description of the

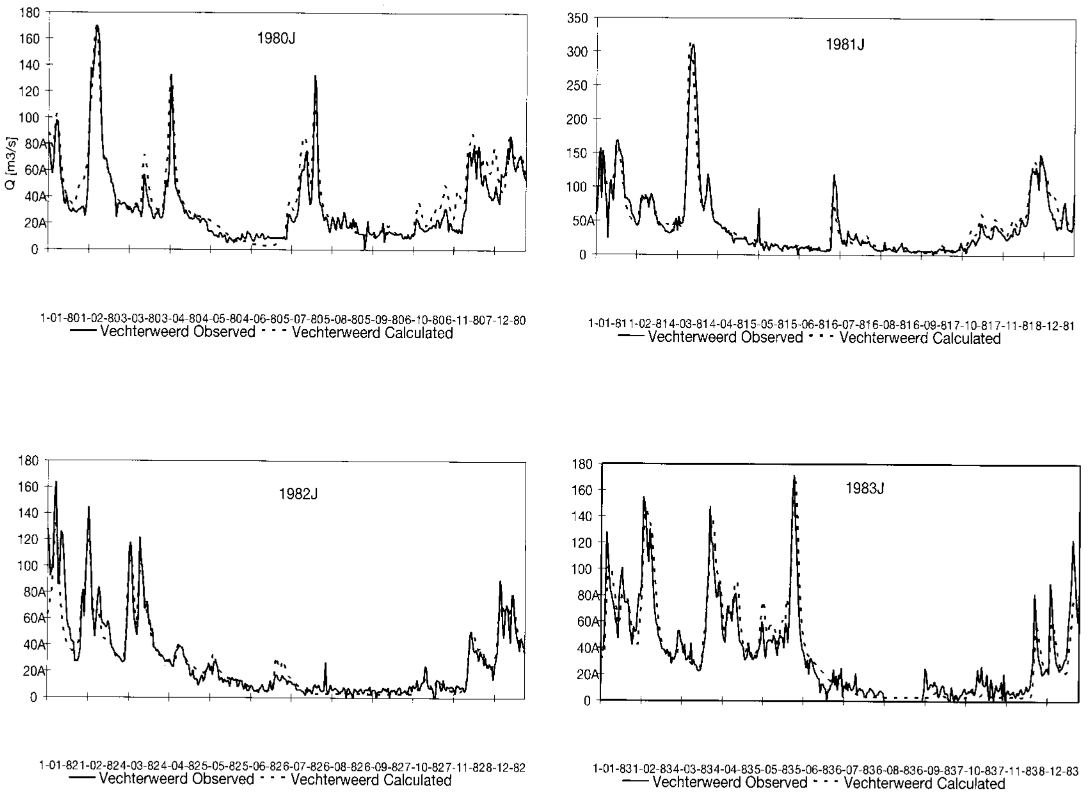


Figure 11.1.4.2. Observed and computed daily discharge For Vechterweerd (whole Vecht catchment) for the years 1980-1983 (in m^3/s)

Table 11.1.4.5 Hydrological characteristics of the reference situation of the Vecht catchment. The winter period (_win) for precipitation P, actual evapotranspiration AE and discharge Q lasts from November – April. The summer period (_sum) concerns May – October. Daily flows exceeding 5% (Q5), 50% (Q50) and 95% (Q95) of time are given. N5 equals the number of days with discharge higher than Q5; N95 equals the number of days with discharge lower than Q95

	Q (mm)			AE	P			
Month	Mean	Minimum	Maximum	Mean	(mm)			
January	49.0	14.1	86.2	8.8	70.0	P_win	382.8	mm
February	37.1	11.2	80.0	13.4	46.3	P_sum	394.9	mm
March	37.6	7.0	86.6	28.5	64.1	AE_win	117.3	mm
April	29.1	7.2	65.2	47.9	51.1	AE_sum	376.9	mm
May	18.7	3.1	54.8	74.0	60.6	Q_win	224.0	mm
June	12.6	2.5	34.5	77.7	73.2	Q_sum	81.1	mm
July	14.2	2.2	52.8	82.8	78.3	Min 7day	19.04	m^3/s
August	9.6	1.9	32.3	72.5	59.7	Max daily	322.05	m^3/s
September	9.9	1.9	37.4	45.8	61.4	Q5	109.43	m^3/s
October	16.2	2.3	58.2	24.2	61.7	Q50	26.86	m^3/s
November	27.1	2.8	60.3	11.0	73.3	Q95	3.00	m^3/s
December	44.1	11.1	116.6	7.7	78.0	N5	475	days
Annual	305.1	67.4	764.8	494.2	777.8	N95	476	days

groundwater storage in the Wageningen Model, but it can also be attributed to disregarding water management measures, which are particularly important in low flow situations. The underestimation of the peak flows may be explained by the time step of one day, which could be still too general for this part of the catchment. Also for Vechterweerd, low flows are again underestimated. Here, higher discharges fit very well, probably because for the entire Vecht catchment, the time step of one day is adequate. The water balance over a number of years is well simulated (cf. table 11.1.4.4). The closing term is in the order of 10 to 15% of the average annual discharge. This is within the expected order of magnitude of the discharge measurement inaccuracy.

11.1.4.2 Model runs with climate change scenarios

The lowland model is used to assess the impact of climate changes on the water balance of the Vecht catchment. Climate change computations are carried out with adapted meteorological data according to the scenarios. The effects of the climate change scenarios are compared with the reference situation. In order to be compatible with the results obtained in other parts of the Rhine catchment, effects of an increased CO_2 concentration and temperature rise on crop parameters were not accounted for.

Reference situation

Simulation of the reference situation, with the present-day climate, was carried out using a record of meteorological data for the 1965 – 1990 period. Figure 11.1.4.3 gives the mean monthly areal precipitation, and actual evapotranspiration as computed with the lowland model over the reference 1965 – 1990 period. Figure 11.1.4.4 shows the computed mean monthly discharge over the 1965 – 1990 period for present-day climate conditions. Minimum discharge occurs in August and September, when evapotranspiration exceeds precipitation. The maximum accumulated actual precipitation shortage is reached by the end of August, and equals 35 mm. The accumulated precipitation shortage continues until the second half of October. Maximum discharge occurs in January. Table 11.1.4.5 summarises hydrological characteristics of the reference situation of the Vecht catchment.

UKHI2050 scenario

Table 11.1.4.6 gives the changes of climatological parameters according to the UKHI-2050 scenario. Figure 11.1.4.5 gives the

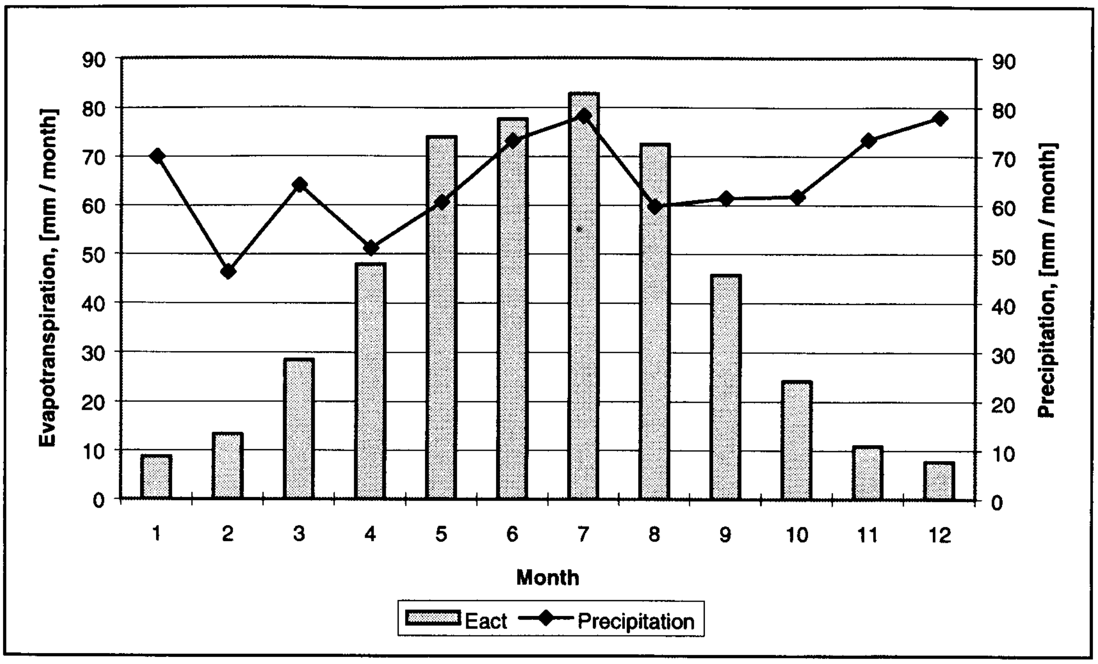


Figure 11.1.4.3 Mean monthly areal precipitation and actual evapotranspiration as computed with the lowland model over the 1965 – 1990 reference period

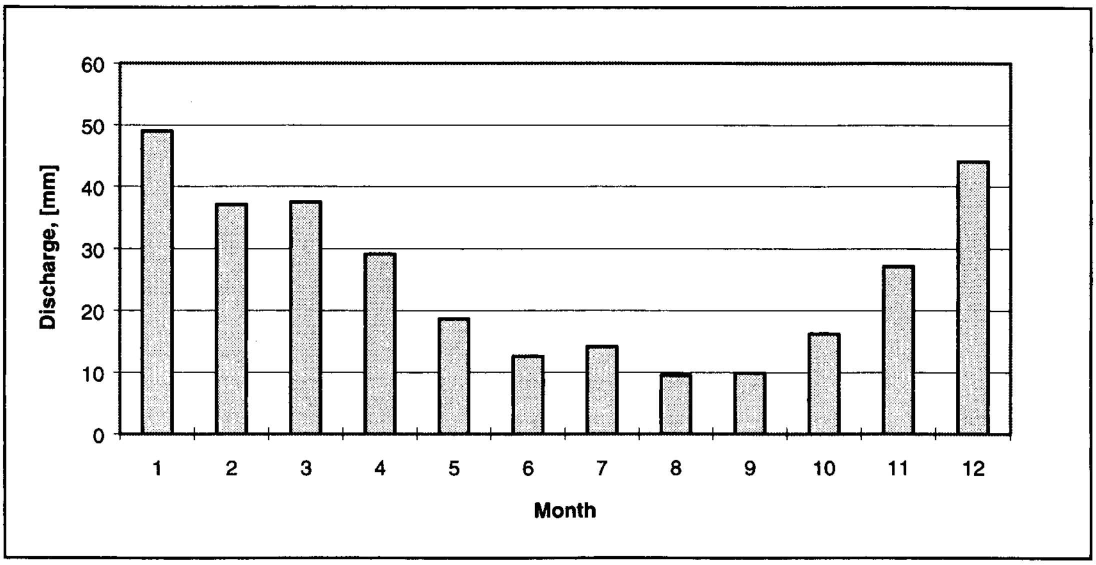


Figure 11.1.4.4 Mean monthly discharge (in mm) of the Overijsselsche Vecht at Vechterweerd in the 1965 – 1990 period, calculated by the model

changes in actual monthly evapotranspiration and precipitation. Figures 11.1.4.6 and 11.1.4.7 show the changes in monthly discharge. The results of the computations with the lowland model with the changed parameters are summarised in table 11.1.4.7.

Actual annual evapotranspiration increases by 11.8% from 494 to 552 mm. Monthly precipitation increases in the winter period up to 20 mm (or 28%) in January. Evapotranspiration increases by about 20% in the winter half year, and 9% in the summer half year. The decrease of precipitation, together with greater evapo-

Table 11.1.4.6 Changes of temperature T (^{0}C), areal average precipitation P (%), sunshine S, wind speed W and relative humidity H (%), according to the UKHI2050 scenario for the Vecht catchment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T	2.7	3.0	2.6	2.1	1.8	1.5	1.4	1.7	1.7	1.7	1.4	2.0
P	28.4	23.2	22.7	17.5	4.3	9.9	4.6	0.1	2.4	9.2	1.9	15.8
S	–22.7	–9.9	–5.2	–1.5	4.7	2.3	0.3	4.6	4.6	4.3	4.6	–2.1
W	7.3	6.4	6.3	4.2	–1.0	5.1	4.3	1.8	–1.8	3.5	–0.9	5.8
H	–3.0	–2.6	–2.9	–1.7	–1.2	–1.9	–2.6	–4.2	–4.0	–1.4	0.4	–1.0

transpiration, reduces discharge in August and September. The actual precipitation shortage amounts to 66 mm by the end of August, which is 30% more than under reference conditions. The precipitation shortage is replenished in November. Annual discharge increases by 8%, which is due to an increase of the winter discharge by 13%, whilst summer discharge is reduced by 1%. The strong increase in precipitation in the winter season raises maximum daily flow by 28% from 322 to 411 m^3/s. During the summer period, low flows become more frequent. Thus, though extreme flows occur more frequently, the discharge distribution over the year does not substantially change.

XCCC2050 scenario

Table 11.1.4.8 gives the changes of climatological parameters according to the XCCC-2050 scenario. Figure 11.1.4.8 gives the changes in actual monthly evapotranspiration and precipitation. Figures 11.1.4.9 and 11.1.4.10 show the changes in monthly discharge. The results of the computations with the lowland model with the changed parameters are summarised in table 11.1.4.9.

The XCCC scenario is more moderate than the UKHI scenario. Actual evapotranspiration only increases in the March to August period. In the rest of the year, it decreases slightly; generally less than 0.5 mm/month. This low increase is because the reduction of sunshine (S) and a higher relative humidity counterbalance the effects of temperature increases and wind speed on actual evapotranspiration. Annual discharge increases by 11%. During the winter period and early spring, monthly discharge increases between 10 and 20%, whilst summer discharge re-

Table 11.1.4.7 Hydrological characteristics for the UKHI2050 scenario of the Vecht catchment. The winter period (_win) for precipitation P, actual evapotranspiration AE and discharge Q lasts from November – April. The summer period (_sum) concerns May to October. Daily flows exceeding 5% (Q5), 50% (Q50) and 95% (Q95) of time are given. N5 equals the number of days with discharge higher than Q5; N95 equals the number of days with discharge lower than Q95

Month	Q (mm) Mean	Minimum	Maximum	AE Mean	P (mm)			
January	58.0	13.7	106.2	13.9	89.8	P_win	450.6	mm
February	43.1	11.1	96.1	17.8	57.1	P_sum	412.7	mm
March	44.5	6.5	105.2	34.2	78.7	AE_win	140.7	mm
April	34.2	7.7	77.4	52.9	60.0	AE_sum	411.7	mm
May	20.3	3.4	60.0	79.7	63.2	Q_win	252.7	mm
June	13.9	2.6	38.1	82.4	80.5	Q_sum	80.3	mm
July	15.1	2.2	55.1	88.4	81.8	Min 7day	19.04	m^3/s
August	8.7	1.9	31.0	80.4	59.8	Max daily	411.27	m^3/s
September	7.7	1.9	29.6	53.1	59.9	Q5	126.94	m^3/s
October	14.7	2.3	55.9	27.7	67.4	Q50	27.34	m^3/s
November	25.7	2.6	59.6	11.5	74.7	Q95	2.93	m^3/s
December	47.3	11.8	130.0	10.3	90.3	N5	686	days
Annual	333.0	67.6	844.3	552.4	863.3	N95	534	days

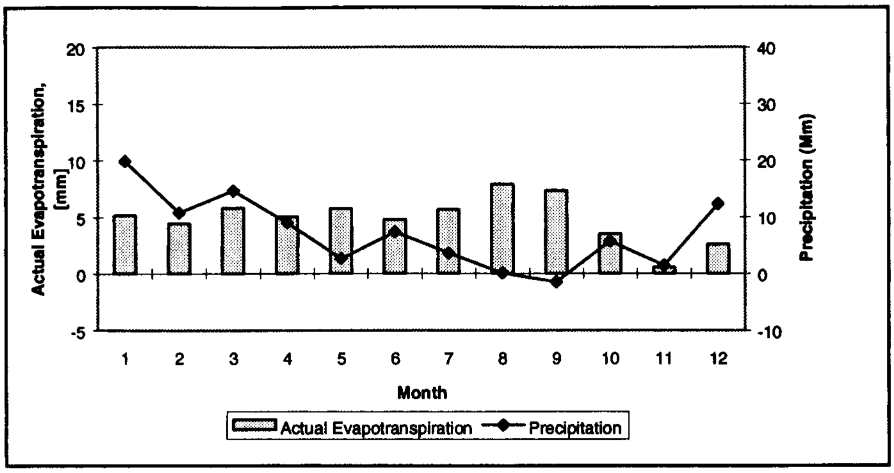


Figure 11.1.4.5 Changes in monthly actual evapotranspiration and precipitation for the Vecht catchment under UKHI2050 conditions

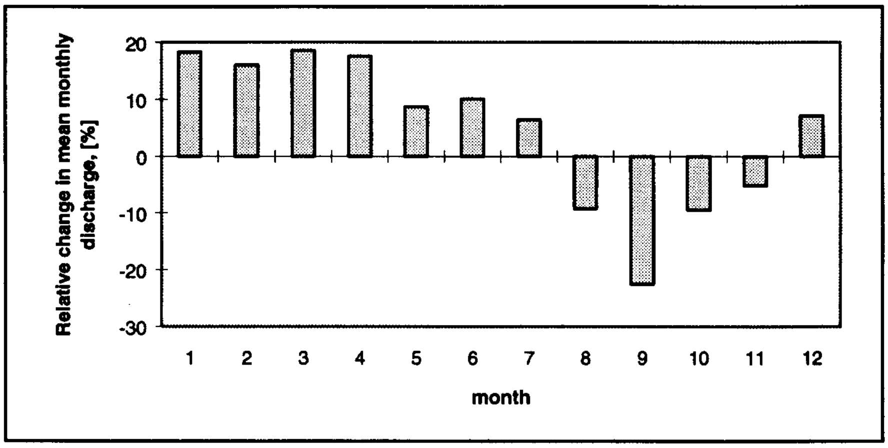


Figure 11.1.4.6 Relative change (in %) of mean monthly discharge for the Vecht under UKHI2050 conditions

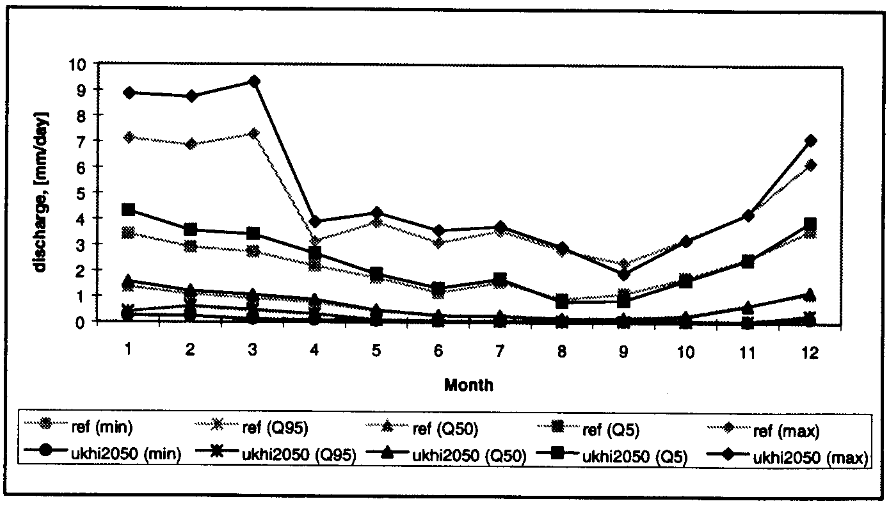


Figure 11.1.4.7 Minimum, Q95, Q50, Q5 and Maximum daily discharges per month for the river Vecht under UKHI2050 conditions, compared with the reference situation

Table 11.1.4.8 Changes of temperature T (in ^{0}C), areal average precipitation P (%), sunshine S, wind speed W and relative humidity H (%), according to the XCCC2050 scenario for the Vecht catchment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T	1.0	1.1	1.1	1.1	0.8	0.9	1.1	1.0	1.1	1.1	1.1	1.0
P	9.0	10.0	15.1	9.5	0.1	–5.7	–0.5	1.4	–3.4	7.0	6.8	10.7
S	–4.3	–5.2	–7.1	–3.7	–0.4	1.6	6.0	2.5	3.7	–1.2	–0.5	–6.8
W	0.6	1.0	4.3	1.8	4.0	–6.6	–4.7	–4.7	–7.0	–0.4	1.2	0.3
H	1.1	2.2	0.8	1.1	1.5	2.0	2.3	1.1	1.7	1.9	1.6	1.5

Table 11.1.4.9 Hydrological characteristics for the XCCC2050 scenario of the Vecht catchment. The winter period (_win) for precipitation P, actual evapotranspiration AE and discharge Q lasts from November – April. The summer period (_sum) concerns May to October. Daily flows exceeding 5% (Q5), 50% (Q50) and 95% (Q95) of time are given. N5 equals the number of days with discharge higher than Q5; N95 equals the number of days with discharge lower than Q95

Month	Q (mm) Mean	Minimum	Maximum	AE Mean	P (mm)			
January	54.9	16.1	98.8	9.0	76.3	P_win	421.6	mm
February	41.6	12.9	89.6	13.1	51.0	P_sum	393.5	mm
March	44.2	8.6	102.0	29.1	73.8	AE_win	118.1	mm
April	33.7	8.4	74.1	49.0	56.0	AE_sum	380.9	mm
May	20.6	3.6	59.0	75.0	60.6	Q_win	254.2	mm
June	12.7	2.6	33.5	78.3	69.0	Q_sum	83.4	mm
July	14.0	2.2	52.5	84.2	77.9	Min 7day	1.0	m^3/s
August	9.5	1.9	32.4	74.1	60.6	Max daily	389.3	m^3/s
September	9.4	1.9	34.6	45.7	59.3	Q5	124.6	m^3/s
October	17.2	2.4	59.8	23.7	66.1	Q50	29.0	m^3/s
November	29.9	3.0	65.2	10.4	78.3	Q95	3.02	m^3/s
December	49.9	13.8	132.4	7.6	86.3	N5	667	days
Annual	337.6	77.2	833.9	499.0	815.1	N95	465	days

mains about the same, with a slight decrease for September. Precipitation shortage lasts from May to August, as under present-day conditions, but becomes more severe. By the end of August it is approx. 43 mm. Maximum daily discharge during the winter period increases, whilst low discharges remain relatively unchanged.

UKTR6675 scenario

Table 11.1.4.10 gives the changes of climatological parameters according to the UKTR-6675 scenario. Figure 11.1.4.11 gives the changes in actual monthly evapotranspiration and precipitation. Figures 11.1.4.12 and 11.1.4.13 show the changes in monthly discharge. The results of the computations with the lowland model with the changed parameters are summarised in table 11.1.4.11.

In this scenario, actual evapotranspiration increases for all months, which can be explained by the strong increase of temperature, and during the late summer period more sunshine and lower relative humidity (see figure 6.10.1). The increase in actual evapotranspiration in winter (31%) is higher than in summer (11%). The annual increase is 15%. Higher evapotranspiration and lower precipitation in summer reduces discharge between April and October. In September the discharge will be 51% less than in the present situation. Precipitation shortage starts in April. The cumulative precipitation shortage amounts to 70 mm in the end of September. This is twice as much as under present-day conditions. Summer discharge decreases by 22%. In the winter period the discharge increases with 5%. On an annual base, discharge is reduced by 2%. High and maximum daily discharges increase in the

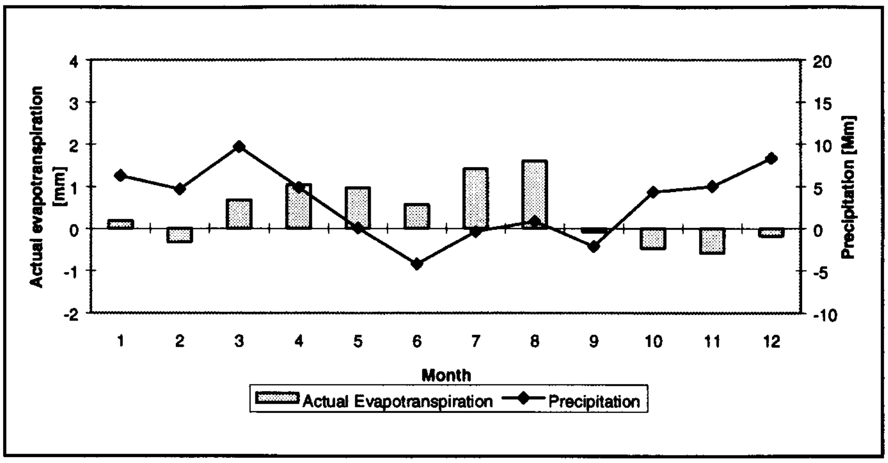


Figure 11.1.4.8 Changes in actual monthly evapotranspiration and precipitation for the Vecht catchment under XCCC-2050 conditions

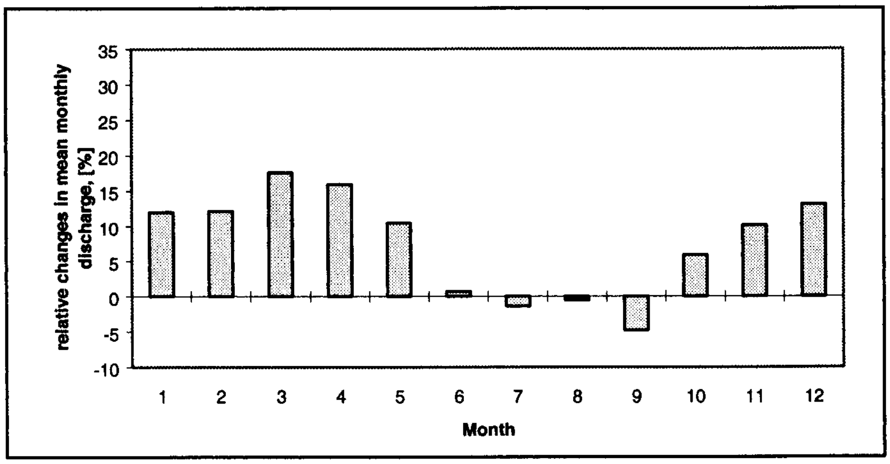


Figure 11.1.4.9 Relative change (in %) of mean monthly discharge for the Vecht under XCCC-2050 conditions

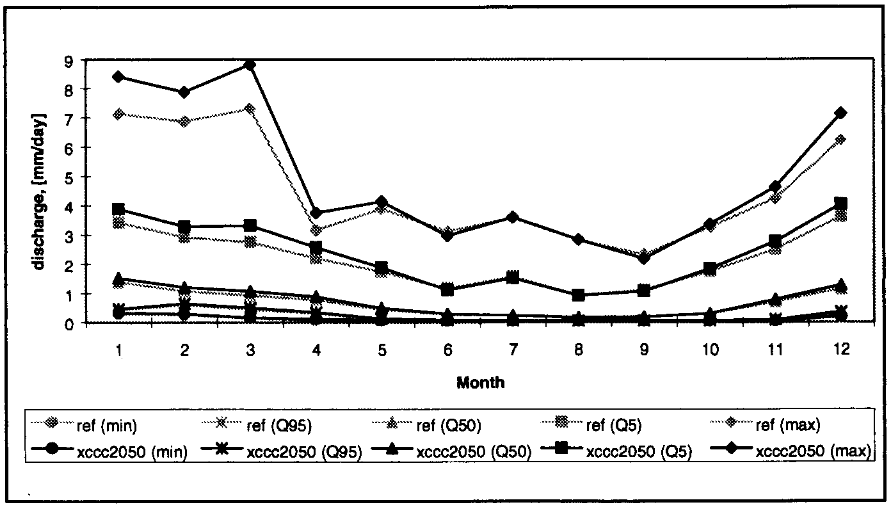


Figure 11.1.4.10 Minimum, Q95, Q50, Q5 and Maximum daily discharges per month for the Vecht river under XCCC-2050 conditions, compared with the reference situation

Table 11.1.4.10 Changes of temperature T (^{0}C), areal average precipitation P (%), sunshine S, wind speed W and relative humidity H (%), according to the UKTR-6675 scenario for the Vecht catchment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T	–2.8	–2.5	–3.2	–1.3	–2.2	–1.6	–1.9	–2.3	–2.6	–1.8	–2.1	–3.0
P	14.0	21.2	23.3	–1.7	–2.2	–8.4	–0.2	–12.7	–10.9	13.1	39.6	–9.9
S	–12.0	–6.4	–20.1	19.2	–3.6	–5.7	–0.0	12.0	10.1	–6.0	–13.7	14.7
W	–2.8	11.4	–4.9	–6.0	–10.9	–7.1	–0.0	–1.1	–1.8	–6.3	10.0	–7.5
H	–6.0	–4.5	–4.8	–4.1	–0.6	–2.2	–0.6	–5.8	–7.3	–1.3	–1.7	–3.8

Table 11.1.4.11 Hydrological characteristics for the UKTR-6675 scenario of the Vecht catchment. The winter period (_win) for precipitation P, actual evapotranspiration AE and discharge Q lasts from November – April. The summer period (_sum) concerns May to October. Daily flows exceeding 5% (Q5), 50% (Q50) and 95% (Q95) of time are given. N5 equals the number of days with discharge higher than Q5; N95 equals the number of days with discharge lower than Q95

	Q (mm)			AE	P			
Month	Mean	Minimum	Maximum	Mean	(mm)			
January	50.4	11.0	93.4	15.7	79.8	P_win	453.2	mm
February	39.5	9.2	91.6	18.9	56.2	P_sum	393.7	mm
March	42.1	5.5	101.3	35.8	79.1	AE_win	153.6	mm
April	28.7	7.3	66.4	55.2	50.2	AE_sum	417.0	mm
May	16.7	2.8	50.0	78.9	59.2	Q_win	235.3	mm
June	11.5	2.4	32.4	83.7	79.3	Q_sum	63.2	mm
July	12.6	2.2	47.9	86.7	78.4	Min 7day	19.0	m^3/s
August	6.4	1.9	25.8	82.7	52.2	Max daily	394.5	m^3/s
September	4.8	1.9	16.8	57.2	54.7	Q5	117.8	m^3/s
October	11.1	2.1	47.1	27.8	69.8	Q50	23.3	m^3/s
November	29.0	2.9	72.5	14.7	102.3	Q95	2.77	m^3/s
December	45.7	10.9	128.3	13.4	85.7	N5	584	days
Annual	298.5	60.0	773.5	570.6	846.9	N95	784	days

winter period, and decrease in the summer half year.

11.1.4.3 Interpretation of the selected scenario results

Though different scenarios were evaluated, their hydrological effects on the river Vecht catchment show several important common characteristics. Precipitation increases during the winter period; in the summer half year, precipitation slightly increases or may be even decreased in some months. The annual evapotranspiration increases, with the greatest absolute increase in summer. This is mainly due to the temperature rise. These changes result in an increase of winter discharge, and a decrease of summer discharge. All scenarios predict an increase of peak flows.

The UKHI and XCCC scenarios for the years 2020, 2050 and 2100 show a linear increase in the changes of the climate parameters, which is of course caused by interpolating the results generated from an equilibrium experiment for 2100 to achieve the changes for shorter time horizons. Increasing the change of climatic variables, particularly of precipitation and temperature, is in a direct way reflected by increasing discharges of the Vecht. This is illustrated for the UKHI-series in figure 11.1.4.14. It is remarkable that there is no shift of the runoff over the season. This means that there are no important temporal sinks or water buffers in the hydrologic system of the river Vecht that are affected by climate change in such a way that the discharge distribution changes over the year. Only a minor effect is found in the precipitation shortage that rises during the summer period. The length of the period of water deficit is much

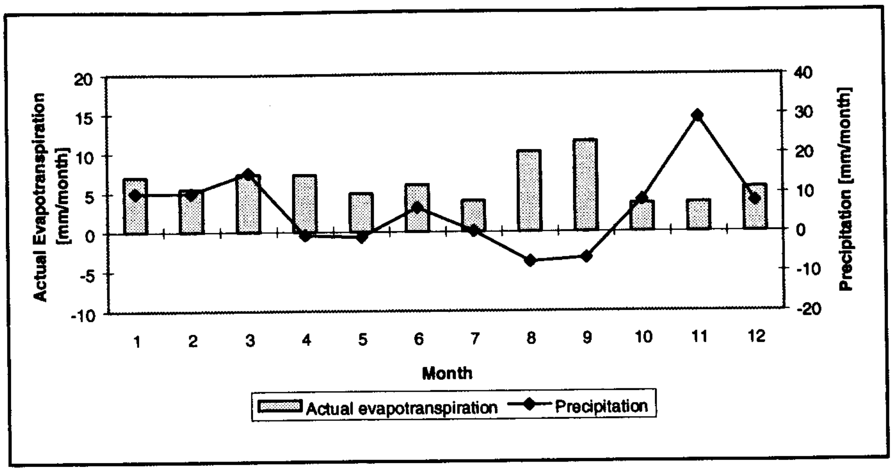


Figure 11.1.4.11 *Changes in actual monthly evapotranspiration and precipitation for the Vecht catchment under UKTR-6675 conditions*

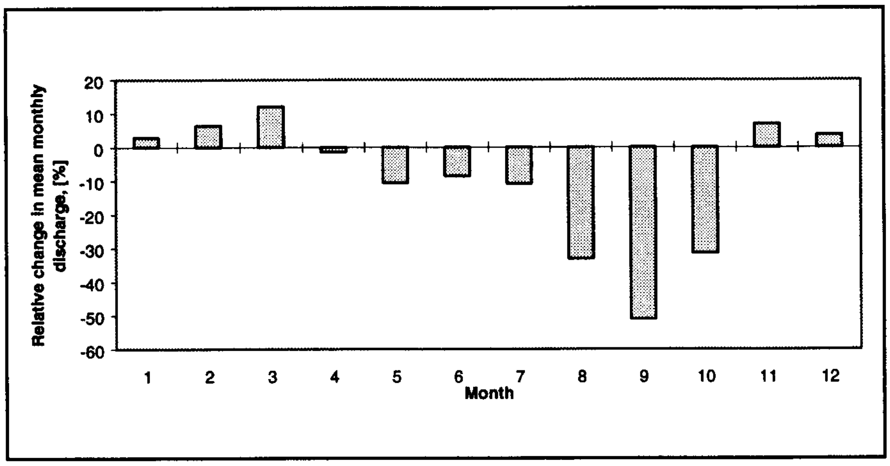


Figure 11.1.4.12 *Relative change (in %) of mean monthly discharge for the Vecht under UKTR6675 conditions*

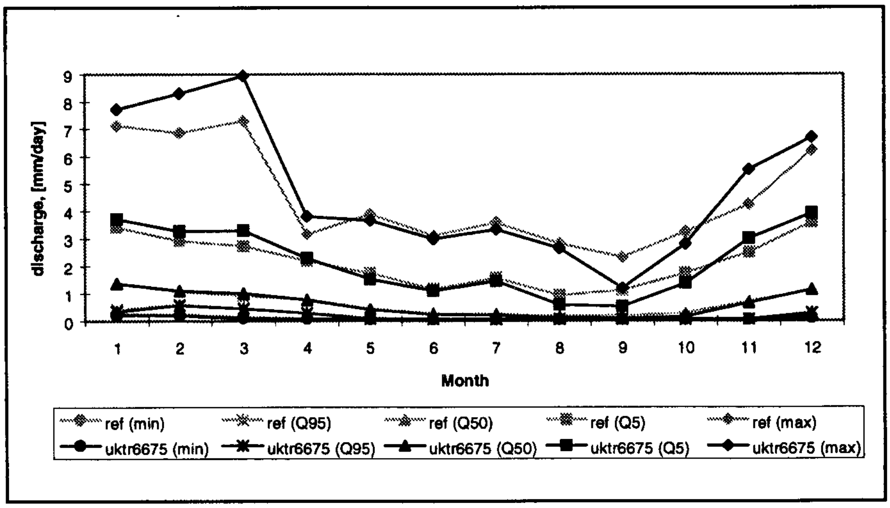


Figure 11.1.4.13 *Minimum, Q95, Q50, Q5 and Maximum daily discharges per month for the Vecht river under UKTR6675 conditions, compared with the reference situation*

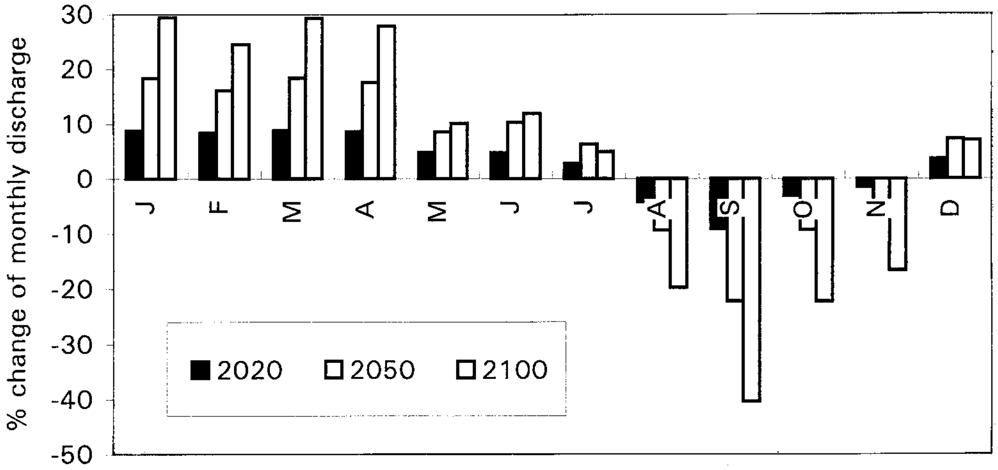


Figure 11.1.4.14 Change in monthly discharge of the Vecht according to the UKHI scenario for increasing climate change

longer for the 2100 scenarios than for the 2020 scenarios.

Though all scenarios indicate the same general trends of the changes, there are several differences between the scenario results that should be mentioned.

- The UKHI scenarios show greater climatological changes than the XCCC scenarios, and thus causes the greatest effects on hydrology.
- In response to the UKHI and UKTR scenarios the Vecht discharge decreases during the months August – November. The XCCC-scenarios result in a runoff decrease from June – September. This shift is mainly due to the more severe and prolonged evapotranspiration during the summer period under UKHI conditions, which results is a greater soil water deficit by the end of the summer.
- The UKHI scenarios result in an increased evapotranspiration over the entire year. The XCCC-scenarios, however, show a reduction of evapotranspiration in the period September – February. This is caused by a relative small increase of the temperature, whilst radiation reduces and the relative humidity increases.
- The average frequency of days with low flow situations that occur during the summer period increases under UKHI and UKTR conditions. The XCCC-scenarios however, predict a reduction of days with low flow.

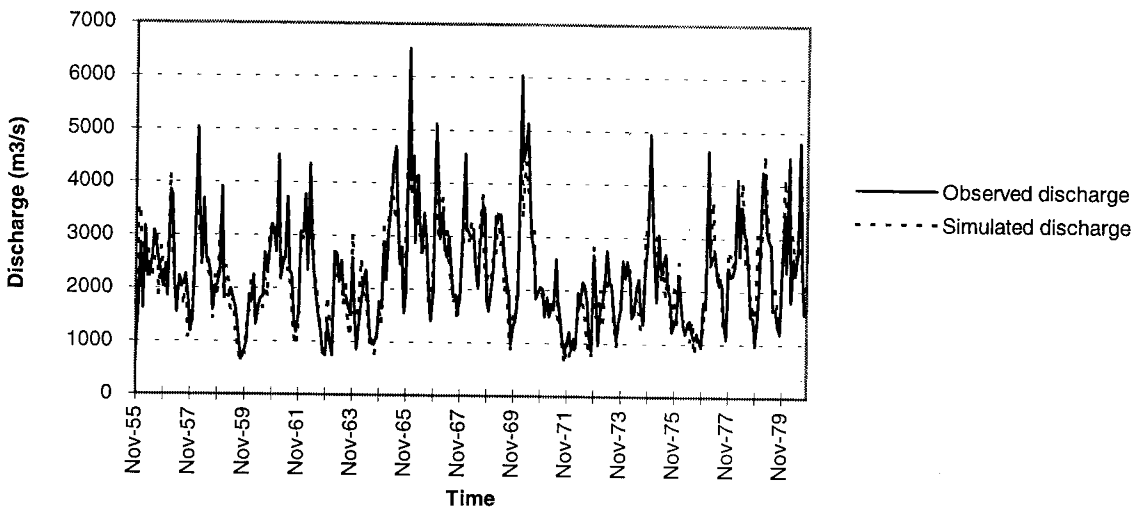
11.2 Results on the regional scale - The Rhine basin

11.2.1 Model calibration and validation

For calibration and validation of the RHINEFLOW model, we used a split sample of a wet and a dry period as proposed by Klemes (1986). Consecutive time series for discharge for all major tributaries are not available for the period before 1956. Therefore the model was calibrated by comparing the calculated and observed hydrographs from the relatively wet November 1965 to October 1970 period. Depending on the tributary, the subbasins received 10-20% more precipitation in this period than the average from 1956-1980. The calibrated model was validated for the period from November 1956 to October 1980. The calculated evapotranspiration and snow water storage in different basin sections were also compared with data observed. Despite its simplicity, the model is quite accurate. Except for one station, annual discharge is estimated by the model within 5 percent of the observed value both for subcatchments (3,000 km^2 and larger), and for the whole catchment (160,000 km^2). Figure 11.2.1 shows calculated and observed hydrographs for the Mosel subcatchment as well as for the entire basin.

Model performance on the month to month variation in streamflow was tested with the coefficient of efficiency, an indication of goodness of fit (Nash and Sutcliff 1970). Depending on

Observed and simulated discharge at Lobith (entire Rhine basin)



Observed and simulated discharge at Cochem (river Mosel)

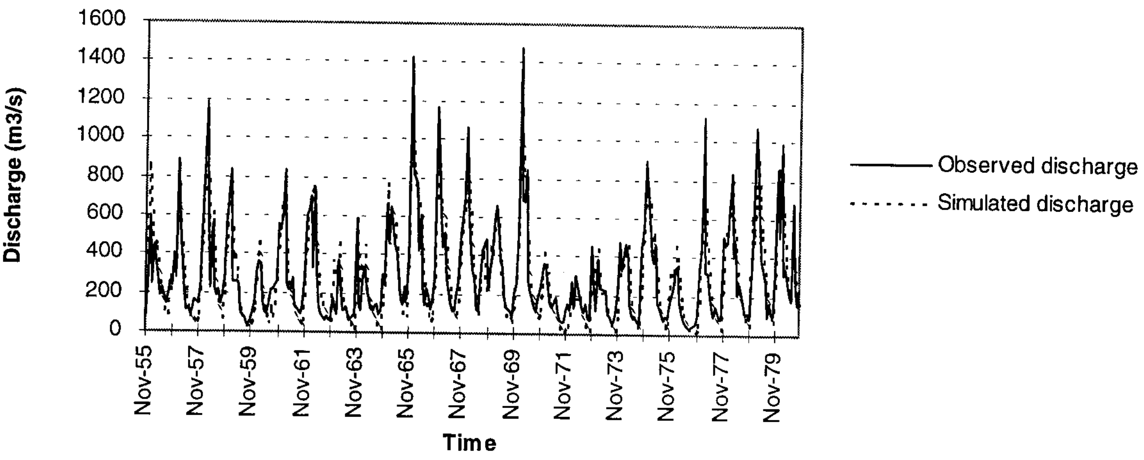


Figure 11.2.1 Model performance for the Rhine basin and for the Mosel basin

the subbasin, the model efficiency is between 0.72 and 0.81, for the entire basin this is 0.77, where a value of 1 represents a perfect fit. The model also showed reasonable results in simulation of evaporation losses and snow water storage (Kwadijk, 1993).

Differences between the results of the RHINE FLOW model and catchment models may be in part attributed to the course resolution of the RHINE FLOW model.

11.2.2 Model runs with climate change scenarios

Table 11.2.1 shows the average monthly changes for precipitation and temperature according to the UKHI and XCCC climate scenarios for the different subbasins as well as for the entire catchment. The results of both climate models suggest that the climate will be changing more and more towards the end of the century. The models also agree on an increasing precipitation in winter and spring and a decreasing precipitation in (late) summer and autumn. Dif-

Table 11.2.1 Climate changes in different basins for 2050

Precipitation change (%)							Temperature change (C)					
	Entire basin		Mosel basin		Alpine Basin		Entire basin		Mosel basin		Alpine Basin	
	UKHI	XCCC	UKHI	XCCC	UKHI	XCCC	UKHI	XCCC	UKHI	XCCC	UKHI	XCCC
Jan	21	14	22	15	15	14	3.0	1.2	3.0	1.1	2.8	1.4
Feb.	17	10	16	10	11	8	3.2	1.4	3.2	1.4	3.1	1.5
Mar	14	13	14	13	8	11	2.6	1.2	2.5	1.1	2.6	1.2
Apr	11	8	12	7	5	8	2.1	0.9	2.0	0.8	2.0	0.9
May	1	2	0	2	0	0	1.7	0.9	1.8	0.8	1.7	1.0
Jun	0	–3	–1	–3	–5	–4	1.6	1.0	1.5	1.0	1.7	1.1
Jul.	3	9	4	–9	7	–11	1.4	1.3	1.5	1.3	1.6	1.5
Aug	–7	–4	–8	–5	–10	–6	2.2	1.1	2.2	1.1	2.5	1.3
Sep	–10	–6	–10	–6	–13	–7	2.2	1.4	2.3	1.4	2.5	1.5
Oct	8	1	9	2	3	–1	2.0	1.2	2.0	1.2	2.2	1.3
Nov	1	10	1	10	3	9	1.4	1.2	1.4	1.2	1.4	1.3
Dec	14	13	14	13	11	13	2.1	1.1	2.1	1.1	2.1	1.2

Table 11.2.2. Discharge changes on an annual basis

	Entire basin			Mosel basin			Alpine subbasin		
	UKHI	XCCC	Control run	UKHI	XCCC	Control run	UKHI	XCCC	Control run
mean	2292	2375	2288	308	320	303	1003	1052	988
Q0.05	4312	4211	3901	849	852	761	1664	1787	1762
Q95	814	885	924	27	28	29	397	424	352
Q. max	6691	6012	5449	1317	1296	1111	2155	2226	2155
Q. min	516	567	621	11	13	14	77	73	86

ferences in temperature change in different parts of the catchments are expected to be small, in the basin as a whole, the temperature is expected to rise. Both models expect precipitation changes to vary spatially over the basin. Larger increases may occur during winter in the northwestern and eastern parts of the basin (Mosel and Neckar) while somewhat larger decreases are expected during summer in the southern parts (Alpine). Striking, however is the difference in magnitude of the climatic changes suggested by each model. The UKHI model envisages much greater climate changes than the XCCC model. The UKHI model expects an increase in winter temperature up to 3.2 degrees Celsius in February while the XCCC scenario suggests that the increase will be limited to 1.4 degrees. Also the UKHI model suggests a larger difference between winter and summer temperature rises than the XCCC does. With respect to precipitation the UKHI model envisages a maximum increase of 21 percent in 2050 while according to the XCCC scenario this increase will be limited to a maximum of 14 percent.

Discharge changes on an annual basis

Table 11.2.2 shows some statistics of the annual discharge at different stations. Changes in mean annual runoff are expected to be minor. The climate simulated by the XCCC model leads to a small increase in runoff in all catchments. The UKHI climate leads to slightly less runoff in the Alps and more runoff in the basin downstream of Rheinfelden, the combination leads to a net increase of the annual runoff. Changes in extreme discharges are represented by the Q0.95, which is the discharge that is exceeded 95% of the time and Q0.05, which represents the discharge that is exceeded only 5% of the time. Both the XCCC and the UKHI modelled climates lead to an increase of the frequency and magnitude of high discharges (Q0.05) at the Rees/Lobith gauging station (entire basin).

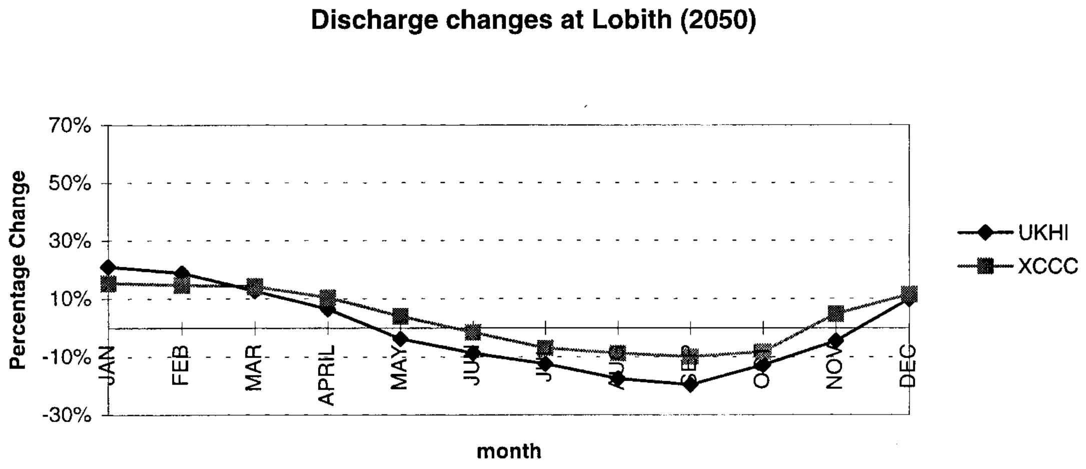


Figure 11.2.2 Monthly discharge changes at the basin outlet (Lobith gauging station)

The results also show a tendency to higher discharges in the German part of the basin. If the climate of the UKHI model is to believed, the results for the Alpine part of the basin suggest a (very) small decrease of extreme runoff, the XCCC climate results in no change or alternatively a (very) small increase.

Low flow periods in the Netherlands may become more common in the next century as the results show a decrease of the Q0.95 at the Rees/Lobith station. In the Swiss part of the basin the sign of the change in Q0.95 varies from basin to basin and from model to model. If the Rheinfelden gauging station is considered, The UKHI climate leads to slightly smaller discharges during low flow conditions, while the XCCC modelled climate leads to slightly greater discharges.

Discharge changes on a seasonal basis

Figure 11.2.2 shows the simulated discharge at the Lobith gauging station according to the UKHI and the XCCC scenario at a time horizon of the year 2050. The figure shows a larger decrease in summer discharge according to the UKHI scenario than according to the XCCC scenario. This can be explained by the greater increase of precipitation in winter and a greater decrease in summer according to the UKHI model. The results in figure 11.2.2 indicate that the climate conditions as simulated by the UKHI model will lead to increased maximum flows in winter at the Lobith gauging station and decreased maximum flows in summer. The results also suggest that minimum discharges will decrease in all seasons except in winter. The results for the XCCC scenario indicate a trend similar to that in the UKHI scenario with respect to maximum discharges, but suggest that minimum discharges may increase during winter and spring and reduce during the other half year.

Figures 11.2.3 and 11.2.4 show the scenario runoff resulting from the climate foreseen by the UKHI and XCCC climate models. The figures show changes for the gauging stations in Rheinfelden and Cochem. The figures illustrate changes in averages as well as changes in extreme monthly discharges. The Rheinfelden gauging station represents the Alpine (35,000 km^2) hydrological regime. The Cochem gauging station is near the outflow of the River Mosel (30,000 km^2) and is representative of the hydrological regime in the western part of the basin area between the Alps and the lowlands.

In the Alpine region the regime is presently governed by high discharges in the early summer and low flows during the winter period. Climate conditions modelled by both the UKHI and the XCCC models lead to an increase of average winter discharges while summer discharges will decrease. The results of the UKHI model suggest less runoff in summer than the XCCC scenario. This is mainly the result of the smaller temperature rise in winter as suggested by the XCCC model, which leads to more snow melt in summer. Differences between summer and winter average discharges seem to be re-

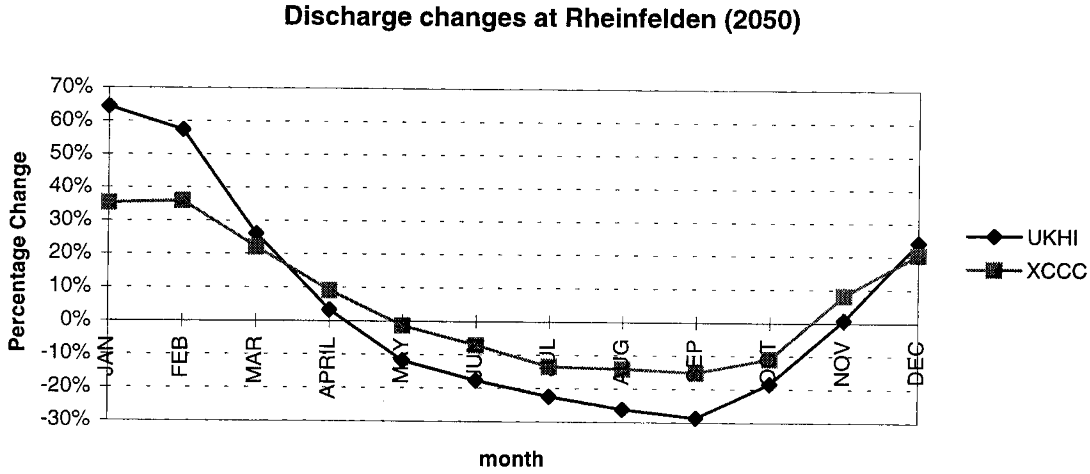


Figure 11.2.3 Discharge changes in the Alpine catchment (Station Rheinfelden)

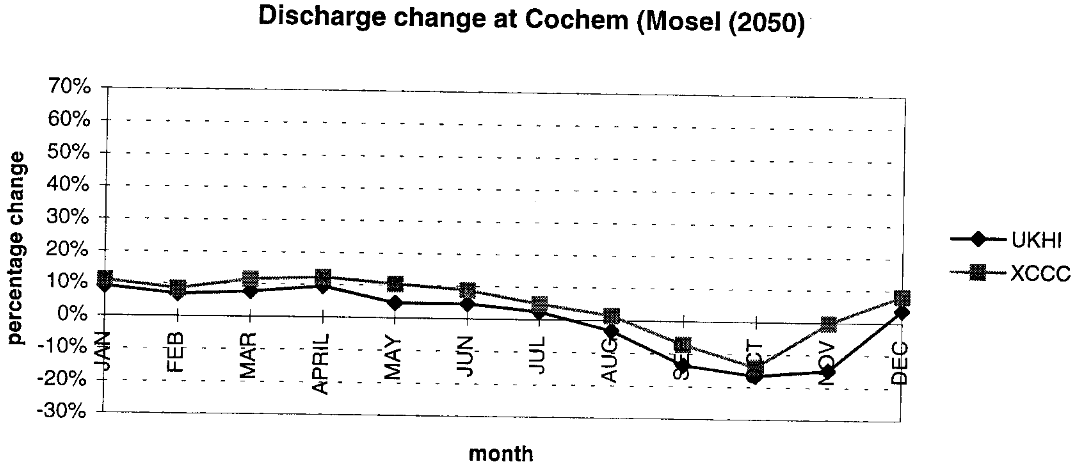


Figure 11.2.4. Changes in the Mosel catchment (station Cochem)

duced. Mean monthly discharge between April and November may reduce which also applies to maximum discharges at that time of the year. Maximum discharges recorded will increase significantly during winter instead of during the summer period and the results suggest that these become larger than present day summer maximum flows. Low flows may occur more frequently during the spring, summer and autumn periods.

In the Mosel basin the scenario results indicate only a slight increase of average winter discharge and almost no discharge changes during summer. Maximum winter discharge seems to increase while maximum summer discharges tend to decrease. The model results do not indicate a change in low flows, although lower flows during January to march may be less frequent as a result of a greater amount of winter rain. In the Mosel basin the effects are small with respect to the expected changes in the Alpine region. Although the UKHI scenario expects a larger increase in winter precipitation that the XCCC model suggests, this is not translated in the discharge changes. This may be the result of the greater evapotranspiration as expected by the UKHI model.

Results based on the UKTR scenario

Figure 11.2.5 shows the discharge changes as result from the climate changes simulated by the UKTR experiment. The results suggest that changes in the German part of the Rhine basin, represented by the Cochem station may result in an increase in winter discharge and decrease in autumn discharges. However, water volume

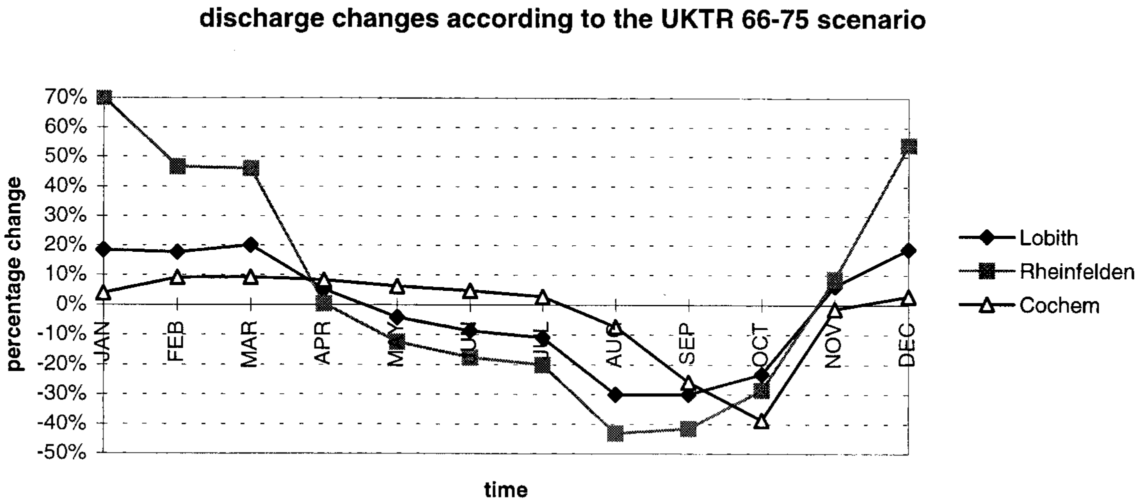


Figure 11.2.5. Changes in the entire basin and alpine area according to the UKTR scenario

changes in autumn are minor as present day runoff is already low during this season. In the Alpine region there is a trend towards greater winter runoff and smaller summer runoff.

11.2.3 Interpretation of selected scenario results

The present river regime is governed by high discharges during the winter period from the low altitude basin section, and by high discharges during spring and summer from the high altitude section. Average maximum flows occur during February and March while October and November show the lowest average flows. This regime can be indicated as a combined snow-fed/rain-fed river. For all scenarios this will shift to a more rain fed river, implying increased average late winter and spring discharges and lower summer and autumn discharges. Therefore for all scenarios, differences between average maximum and minimum flows will increase.

A study into the impact of climate changes on the Rhine river was recently published (Kwadijk and Rotmans, 1995). This study used climate scenarios that were based on greenhouse gas emission scenarios. These scenarios include the Business as Usual (BaU) and Accelerated Policy (AP) scenarios (IPCC, 1990). In addition, a quantitative estimation of the uncertainties around the BaU best guess was produced. The results from the 2050 UKHI and XCCC scenarios indicate the same trend as this best guess. The discharges as calculated from both climate scenarios are within the uncertainty range defined in this earlier study. Like Wigley and Jones (1984), Kwadijk (1993) concluded that with respect to runoff changes in the Rhine basin, precipitation changes were more significant than temperature changes. The projections of the UKHI and XCCC climate change, however, suggest that both may become significant within the next century. Although the UKHI model envisages greater winter precipitation than the XCCC scenario, this does not lead to greater annual runoff. This is partly the result of the expected decrease in summer precipitation envisaged by the UKHI model but is also caused by a greater evapotranspiration as a result of the higher temperatures.

12 Synthesis of the model results

General trends

As has been outlined in the previous chapters, all scenario simulation results generally tend in the same direction, irrespective of the scenarios and the hydrological models used. A general tendency is the shift of the hydrological regime in the entire Rhine basin: in the upper Alpine part a smoothing effect between summer and winter discharge can be observed, while in the lower parts the summer-winter differences are amplified. The main trends that were found per subregion within the Rhine basin are:

- In the Alpine area, higher temperatures will lead to a lower accumulation of snow in the winter half year. This results in higher winter discharges, and lower summer discharges. In addition, winter precipitation increases much more than summer precipitation. Higher temperatures will increase evapotranspiration, particularly during summer. This increase is larger than the precipitation increase, resulting in an overall reduction of annual runoff. When comparing responses of different basins in more detail, the results suggest that between basins large differences in response may occur. Depending on the altitude ranges of the catchments, the maximum daily flow may either increase or decrease. Winter peak flows in the high-alpine area generally increase, especially for floods with a return period of more than 10 years. In pre-alpine areas, this increase is less significant. Changes in summer peak flows cannot be well determined as these are largely generated by convective storms, and demand a much finer temporal and spatial modelling scale. Summer minima decrease in all cases. It should be mentioned that the influence of Alpine glaciers has not been considered in the catchment studies. In the long term, the increased ablation of Alpine glaciers will contribute to the severity of low flows in the upper and middle parts of the Rhine basin. The results demonstrate that estimating effects in larger alpine areas from the response in small catchments is a precarious task.
- In the German Middle Mountains, the investigated catchments do not demonstrate such a strong seasonal shift in the discharge as in the Alps. The changes in discharge are controlled by the balance between increased precipitation on the one hand, and increased evapotranspiration rates due to higher temperatures on the other hand. The balance between the two depends both on the expected climate changes and on the present water balance, governed by the present climate and land use. In the investigated cases, the increased evapotranspiration seems to counterbalance the higher precipitation, resulting only in a slight reduction of average runoff during winter, and a much greater reduction during summer. Depending on the severity of net precipitation shortage in summer, the soil water deficit at the end of summer becomes larger, and results in a considerable time lag (weeks to months) until it is refilled by precipitation. Peak flows resulting from heavy rainfall and convective thunderstorms, however, are expected to increase. In the middle mountain area, the differences in response between catchments are considerably smaller than in the Alps.
- In the lowland area, increased winter precipitation will cause higher winter discharge. During summer, higher evapotranspiration causes a net precipitation deficit, resulting in lower discharge. Here too it may take several weeks before the deficit is replenished by precipitation.

Different scenarios

When comparing responses between different climate scenarios, the UKHI scenarios generally result in greater changes than the XCCC scenarios. Nevertheless, the trends indicated are the same. In addition, differences between catchment response occur (figure 12.1). This may be due to the diverse physical characteristics of the subcatchments. Slight differences may also result from using different reference periods for the studies (table 12.1). The use of different reference periods was done for practical reasons, i.e. the availability of data. The gain of using one standardised reference period for all studies seemed very questionable in view of all other assumptions and adopted simplicity in the scenario constructions.

Different models

When comparing the high resolution models with the RHINEFLOW model, similar trends are found on a monthly basis. The degree of the changes, however, may be different. To

Table 12.1 Simulation periods for catchments of the Rhine

Basin	Simulation period
Rhine (entire basin)	1955 - 1980
Blies (Germany)	1962 - 1989
Prüm (Germany)	1975 - 1984
Saar (Germany)	1962 - 1989
Ergolz, Broye, Murg (Switzerland)	1981 - 1993
Thur (Switzerland)	1981 - 1995
Vecht (Netherlands)	1965 - 1990

illustrate this, the changes in monthly discharge according to the UKHI2050 scenario according to both RHINEFLOW and the detailed models are shown in figure 12.1 for different parts of the basin. The differences between the results of RHINEFLOW and the detailed models can be attributed to several factors. The catchments of the detailed models are considerably smaller than the subsections of the Rhine basin from the RHINEFLOW model that were considered for comparison with the detailed models. As a result, typical characteristics and local conditions, such as elevation, geology, land use within a subcatchment may be different from the average situation in the larger area evaluated by the RHINEFLOW model. In the Alpine area this may result in different estimates in the amount of snow storage during winter. Differences in snow storage during winter may also explain part of the differences found among the detailed models in this mountain area. In addition, using monthly averages of temperature and precipitation in the RHINEFLOW model may occasionally result in different estimates of snow storage and snow melt. This may explain the difference between the higher winter discharge according to the RHINEFLOW model. The differences for the German Middle Mountains (Saar basin) seem to be caused by the representation of evapotranspiration processes. Generally, the detailed models suggest an overall decrease between 5 percent in winter and 25 percent in autumn, while the RHINEFLOW model suggests an increase in winter runoff, and a much smaller decrease during summer. Differences between the RHINEFLOW results for the area downstream of Andernach and the Vecht basin in the lowland part of the basin can be both explained by the physical differences between these areas, and by different ways of representing evapotranspiration. The effects seem to be strongest for the summer period. This might be caused by the role of groundwater. In the Vecht basin, groundwater flow contributes substantially to the runoff in this river. This ground water flow is well represented by the Vecht model, while in the RHINEFLOW model groundwater flow is represented simply by a linear recession equation.

Peak flows

From the model results, it is difficult to achieve reliable estimates of changes in (extreme) peak flows. Peak flows in small areas depend very much on precipitation characteristics, such as convective storms and length of wet periods. In this study changes in precipitation were implemented in a rather straightforward way, as the percentage of precipitation increase has been evenly distributed over the whole range of present day precipitation. This may lead to inconsistent estimates of precipitation extremes under changed climate conditions. In addition, the method assumes that the number of days with precipitation remains unchanged. Under changed climate conditions with higher temperatures, it is expected, that convective high intensity precipitation may occur more frequently. However, as the size of such storms is small, estimations of floods in larger catchments are less sensitive for individual events. Floods in larger catchments occur mainly in winter as result of large scale frontal rainfall. Since in winter both rainfall and the melt water runoff contribution from the Alps are expected to increase, peak flows in the Rhine river will increase. Unfortunately, changes in discharge extremes could not be determined directly with the RHINEFLOW model, because peak flows are masked by the low temporal resolution of the model. Alternatively, a statistical method was applied to achieve estimates of peak flows in the downstream part of the Rhine basin.

Low flows

The reliability of the simulation results is higher for low flow conditions, because periods of low flow are characterised by a lower temporal variability (in the order of weeks), which is more in accordance with the temporal resolution of the climate scenarios. A major uncertainty for estimates of low flow is caused by uncertainty in evapotranspiration. The changes in transpiration by plants and the effect of increased CO_2 concentrations on the stomatal resistance and transpiration efficiency of the plant leaves are still not well known.

Perspectives for model improvements

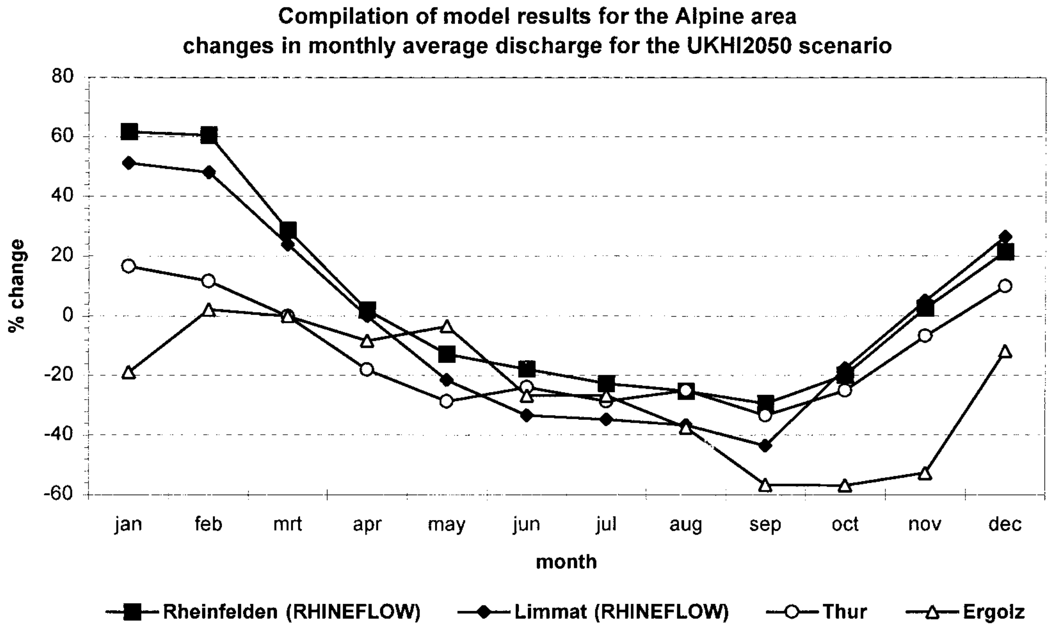
Improvements of model results for the Rhine basin should focus on the following issues:

- Improved scenarios for precipitation are required, both with high spatial and temporal resolution.
- Estimates of peak flow probabilities in high Alpine areas demand both precipitation scenarios and hydrological models on a hourly basis with a high spatial resolution.
- Detailed models with a daily time step should be developed for larger subcatchments, and finally result in a model for the entire basin.
- A further analysis of changes in evapotranspiration, particularly in combination with a higher transpiration efficiency due to higher CO_2 concentrations needs to be carried out.
- The time step of the RHINEFLOW model should be reduced to 10 days. In addition, the model concept used by RHINEFLOW for calculating evapotranspiration should be improved.

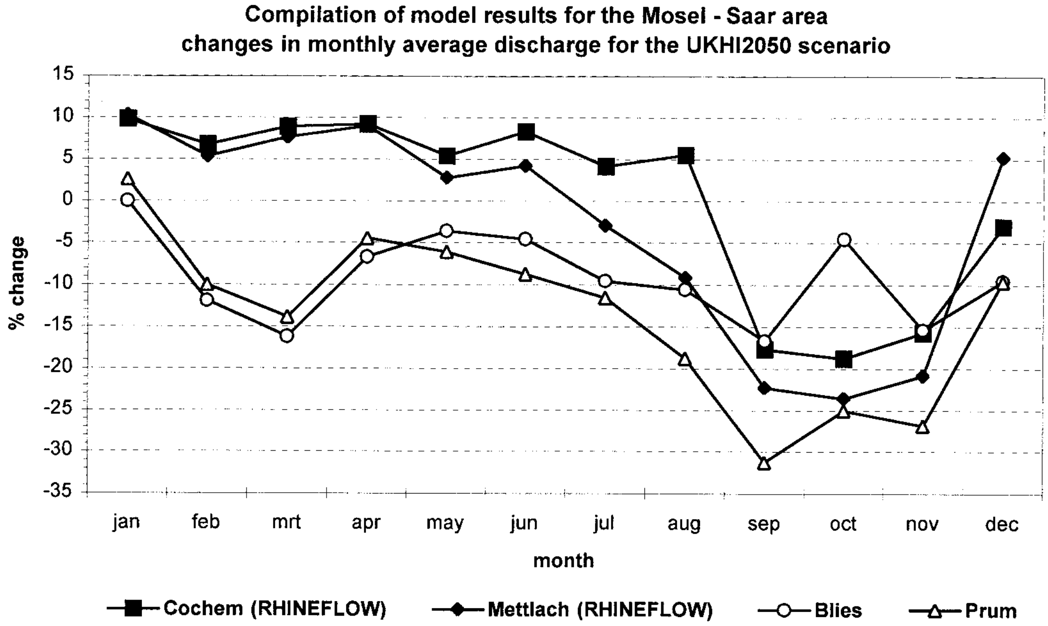
Conclusions

The bandwidth of the simulation results is wide. This is the result of a combination of factors, including: insufficient resolution and parametrisation of climate scenarios, insufficient knowledge of atmospheric processes on a much more detailed spatial and temporal scale, and in small catchments hydrological responses on an hourly basis. Even for the RHINEFLOW model, with its coarse temporal and spatial resolution, the bandwidth of the simulation results is large. As a consequence, the simulation results allow the recommendation of measures only in a more general way.

Despite the caution which has been voiced by the authors of the study, a remarkable progress has been achieved by the combination of climate change scenarios and hydrological models used in the present study. Prior to this study, estimates of climate change impact on the Rhine basin were not supported by plausible and consistent sets of climate scenarios, nor by models based on a scientific understanding of the hydrological response. In addition, previous estimates did not provide a plausible quantification of the changes. The present study provided quantitative estimates of the hydrological changes that may be expected, in spite of the uncertainties in the climate scenarios. These results therefore provide a basis for the need and the direction of water management measures. The implications for water management and an indication of policy recommendations are described in chapter 15.



Compilation of model results for the Alpine area
changes in monthly average discharge for the UKHI2050 scenario



Compilation of model results for the Mosel - Saar area
changes in monthly average discharge for the UKHI2050 scenario

Figure 12.1

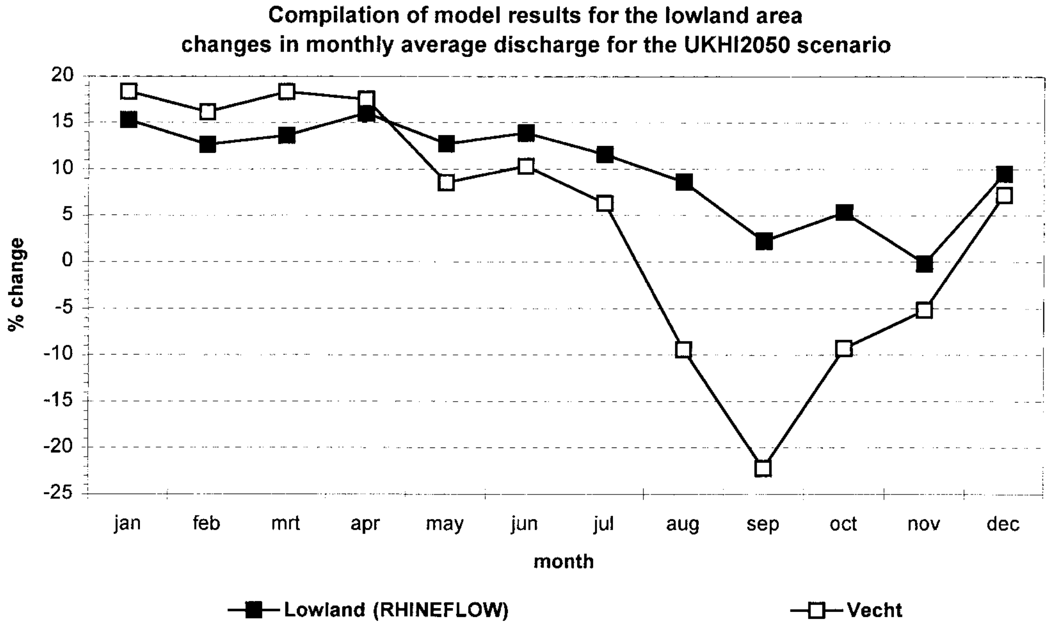


Figure 12.1 Continued

13 Land use scenarios in the Rhine basin

13.1 Introduction

In addition to the effect of climate changes on the hydrology of the Rhine basin, the effects of land use changes were also considered. Land use affects interception of precipitation, it influences the ratio between infiltration and surface runoff, and it determines evapotranspiration to a large extent. It is therefore expected to be an important parameter in hydrological processes.

Under present-day conditions, about half of the total area of the Rhine basin is used for agriculture, about one third is covered with forest, and 11% is built-up area. Increased atmospheric CO_2 levels, and the associated climate changes affect growth and evapotranspiration of plants. For natural vegetation this could mean that existing ecosystems shift, alter their species composition, or even completely disappear. For agricultural crops, this may lead to an increased production, a change of cropping patterns, and the introduction of new varieties. Whether changed climate conditions indeed lead to changes in land use, largely depends on economic, political, demographic, and technical developments. These are here referred to as 'autonomous' changes.

Land use scenarios taking into account the effects of climate change in combination with autonomous developments were not previously available. Therefore, they were developed for this study by the Winand Staring Centre, at the request of the Institute of Inland Water Management and Waste Water Treatment.

13.2 Crop production

In a preliminary study, Wolf and Van Diepen (1991) concluded that a higher CO_2 concentration, an increase in temperature, and a small change in precipitation during the growing season do not bring about limitations for crop growth, but may rather improve the circumstances for the cultivation of presently grown crops. Most crops grown in Western Europe are of the so-called C3 type, for which the CO_2 concentration is suboptimal. A higher CO_2 concentration acts as a fertiliser and increases the assimilation rate. For so-called C4 crops, of which maize is the only important representative, the CO_2 concentration is already optimal under present-day conditions, hence an increase in assimilation rate will not occur. An increase in temperature is favourable for crop production where temperature conditions are sub-optimal. Besides production, CO_2 influences the water use efficiency. With higher CO_2 concentrations, the stomata of leaves have to be opened less to take up the same amount of CO_2. This results in a higher transpiration efficiency, resulting in a lower loss of water. For the overall water use of crops, the increase in production partly counterbalances the increase in water use efficiency, because the leaf surface increases.

13.3 Development of land use change scenarios

Though changed climate conditions will play a role, land use changes in the Rhine Basin will be largely determined by autonomous developments. The development of land use scenarios for the Rhine basin was therefore divided in two parts, a biophysical part, and a socio-economic part. For this study, the IPCC 'Business as Usual' (BaU) climate scenario (IPCC, 1990; Kwadijk, 1993) was used. This scenario assumes a doubling of the CO_2 concentration, resulting in an increase in temperature of 1.5°C in summer and 2°C in winter. Precipitation remains unchanged during summer and increases by 10% during winter. The target period is around 2050.

Biophysical part

The biophysical part of the study aimed at assessing the effect of doubling of the CO_2 concentration, in combination with a changed climate, on crop production, crop water use and cropping calendar (Roetter, 1994; Roetter and Van Diepen, 1994). Mean temperature, precipitation and annual temperature amplitude are the main factors that determine the regional differentiation of agricultural crops and natural vegetation. To cover the regional differences in climate and soil in the Rhine basin, a biophysical classification system was developed, based on meteorological data for 53 stations and a digitised altitude map. The bioclimatic system for

the Rhine basin uses the following criteria:
1) annual mean temperature (seven classes),
2) annual mean temperature amplitude (four classes),
3) annual mean temperature of the coldest month (five classes),
4) annual mean precipitation (five classes).

In addition, a soil suitability classification was carried out using a digitised soil map as a basis. Soil mapping units were clustered in soil suitability groups based on slope class, soil texture, depth, moisture retention characteristics and soil genesis. Five land suitability classes were distinguished. Biophysical types were obtained by combining the bioclimatic types with soil suitability groups. This was done for present and possible future conditions. Using a crop growth model, WOFOST, potential and water-limited yields were computed for seven major crops in the Rhine basin: winter wheat, silage maize, barley, oil seed, potato, sugar beet and rye grass, for present and possible future conditions (Roetter and Van Diepen, 1994). Computations were carried out using meteorological data from 18 weather stations, representing the predominant base-line climatic types, and for two soil types representing the soil moisture and retention characteristics of the soil suitability groups. Simulation results for present and possible future climate were combined into changes in land suitability and attainable yields in the Rhine basin.

Socio-economic part

The socio-economic part examined the influence of autonomous developments on land use, and combined this with the results of the biophysical part to scenarios or projections (Veeneklaas et al., 1994). The Rhine basin was divided in 13 regions, based on the NUTS-1 division of the European Union (EU). A ‘Central Projection’ scenario was defined, based on historic secular trends, technical and scientific restrictions for crop production, and some ‘basic assumptions’ (Veeneklaas et al., 1994). Basic assumptions in the Central Projection for urban land use are that population growth is marginal, but the amount of urban land per inhabitant will increase. For agriculture it is assumed that technical progress continues, and that regional differences in the ratio between actual and water-limited production will level out. By 2050, yield levels will have reached 90% of the water-limited yield in all regions. The common market of agricultural products within the EU will remain. World trade in agricultural products will not expand dramatically, and protection of home markets for food will not disappear. Stricter environmental regulations are expected for agricultural production. In addition to the Central Projection, a Plus and a Minus variant were defined. The Plus variant assumes maximum urban and agricultural claims on land, and the Minus variant assumes minimum claims. These projections were evaluated for both present and changed climate conditions.

To implement the projections, a hierarchical scheme was applied. Urban land needs and nature claims as defined in national policy plans have the highest priority. Second in line are agricultural land requirements, and lowest priority is given to forest and other land use. This hierarchy is based on the price of land paid by the different categories. For agriculture a second hierarchical scheme was nested, based on the profitability and the required quality of land. These are (arranged by decreasing priority): horticulture and permanent crops, root crops, cereals, and, with lowest priority, grassland and fodder crops.

13.4 Results

Biophysical part: changes in land use potentials

Simulations with the WOFOST model demonstrated that, in general, crop production will increase in response to the assumed climate change. For the group of soils with an available water capacity of 70 mm, the average production for the Rhine area increases by 40% for winter wheat, 33% for rye-grass, 25% for sugar beets, and 12% for silage maize.

Soil and terrain characteristics, in combination with mean annual temperature, are the most decisive factors for land suitability. If climate changes according to the described BaU ‘best-guess’ scenario, the areal percentages of land suitability classes change as described in table 13.1. The ‘very high’ class increases from 1.3 to 38.6%. The percentages of the other classes decrease. The assumed climate change thus has a

Table 13.1 Areal percentages of land suitability classes for unchanged and changed climate conditions (Roetter & van Diepen, 1994)

and suitability class	percentage of total area, (%)		change, (%)
	unchanged climate	changed climate	
very high	1.3	38.6	+37.3
high	28.1	3.7	−24.4
moderate	41.8	37.3	−4.5
marginal	8.8	0.7	−8.1
unsuitable	20.0	19.7	−0.3

Table13.2 Changes in areas of urban and agricultural land use for unchanged and changed climate conditions, for three variants with respect to the basic assumptions, for the 2040-2050 decade, in million ha and percentages (Veeneklaas et al., 1994)

	Central Projection		Minu variant		Plus variant	
Land use	unchanged	changed climate	unchanged	changed climate	unchanged	changed climate
Agriculture	−1.57 −20%	−1.83 −24%	−2.67 −34%	−2.84 −37%	−1.26 −16%	−1.52 −20%
Urban	+0.68 +32%	+0.68 +32%	−0.18 −9%	−0.18 −9%	+1.39 +66%	+1.39 +66%
Urban+ agriculture	−0.89 −9%	−1.15 −12%	−2.85 −29%	−3.02 −31%	+0.13 +1%	−0.13 −1%

positive effect on the overall suitability of land for cultivation of current crops and tree species.

Socio-economic part: land use projections

The area of land used for agriculture is expected to decrease. This is the result of ongoing increases in productivity per hectare, and a stagnant demand associated with the expected low population growth.

The expected changes for the entire Rhine basin are listed in table 13.2. The basic assumptions of the Central Projection result in an increase in urban land use. The Plus variant results in a larger increase of urban land use, whilst in the Minus variant urban area decreases. Under changed climate conditions the decrease in the agricultural area is even larger, because production levels increase and hence, less land is needed. Especially, the acreage of cereals and, to a lesser extent, potatoes decrease. This is because physical conditions for production of cereals are suboptimal, and competition with areas outside the EU is great. The crop area of beets will slightly increase, in response to a greater demand of fodder beets for cattle. In the Central Projection about one million hectares would become available for non-agricultural use, in the Minus variant this is 3 million hectare and in the Plus variant no substantial surplus would be available. Changed climate conditions alone add approximately 0.2 million hectares. In Germany and in the French part of the Rhine basin large parts of the agricultural land will be vacated. These are mainly the areas where cereals are grown presently. The vacated areas could be used for afforestation, especially if different functions such as timber production, recreation and nature can be combined.

13.5 Implications for hydrology: Overijsselsche Vecht case study

To evaluate the effects of land use change on hydrology, a case study was carried out for the Overijsselsche Vecht catchment. Computations with the lowland model were carried out with changed land use (and hydrological units)

Table 13.3 Land use distribution (% of total area) in the Vecht catchment for the present situation and for the assumed land use scenario (Minus variant of the Central Projection with changed climate)

Land use	Present situation	Changed land use	Land use	Present situation	Changed land use
Potatoes	3	1	Deciduous forest	7	16
Sugar beets	2	1	Coniferous forest	6	15
Cereals	2	1	Nature	6	15
Maize	15	8	Bare soil	6	6
Grass	45	32	Urban area	6	6

in combination with changed climate according to the UKHI 2050 scenario. It was assumed that land use changes do not affect the transport of water through the soil towards the drainage system. The parameters of the rainfall-runoff model were not changed. Also, the parameters of the sewer system and the daily water consumption per caput were kept constant.

Construction of land use scenarios for the Vecht catchment

To study the effect of land use changes on the water balance of the Vecht catchment with the lowland model, land use was changed according to the Minus variant of the Central Projection with changed climate conditions. In this scenario the total agricultural area is reduced by about 35%. Part of the agricultural land that is taken out of production will be used for nature reserves. Natural areas will increase in size to 10% of the total agricultural area, which is part of the Netherlands policy plan on nature. It is assumed that the remaining part of the abandoned agricultural area will be planted with coniferous and with deciduous forest in a 50-50 ratio. The total urban area in the Netherlands-East region was not changed for the computations with the Vecht model. For the sealed area module the change in the number of inhabitants is relevant. In the Minus variant the population in the Netherlands-East region decreases by 4%. The land use scenario was implemented for the subcatchments of the Overijsselsche Vecht by adapting the hydrological units of each subcatchment according to the expected changes in the area of different land use types. The effect on the land use distribution in the Vecht catchment is given in table 13.3.

Result of the UKHI 2050 scenario with land use change

Land use changes affect the discharges by changes in evapotranspiration. Under UKHI 2050 climate conditions, land use changes cause an increase in annual evapotranspiration by about 7%. In figure 13.1 the changes in actual monthly evapotranspiration are given for the UKHI-2050 scenario with and without land use changes, compared with the present situation. During the winter period, evapotranspiration and interception are increased because of the increase in area of coniferous forest. The decreased evapotranspiration in July is because evapotranspiration of agricultural crops is larger than of forest in the growing season. The precipitation deficit is hardly changed during that period, since that the decrease in evapotranspiration is small in relative terms.

The increase in evapotranspiration reduces annual discharge under UKHI 2050 conditions by 10%. Figure 13.2 shows the changes of monthly discharge, both without and including land use changes, compared with the present situation. The increase in winter discharge, resulting from the UKHI-2050 climate change, is reduced considerably. During the summer periods, discharge is even more reduced than under climate change only. The reduction of evapotranspiration in July did not result in a higher discharge in this month. This is due to a lower base flow that results from the increased evapotranspiration in the previous months.

13.6 Conclusions

A doubling of the CO_2 content and an increase in temperature seem to have a positive

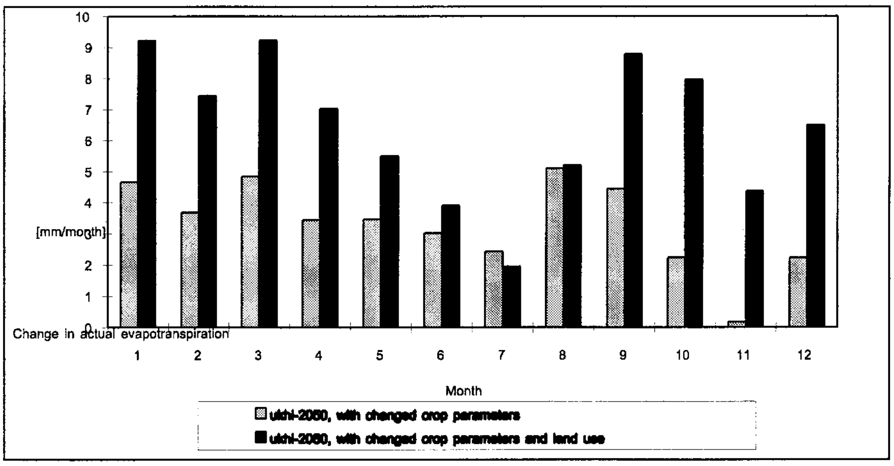


Figure 13.1. Changes in monthly evapotranspiration under UKHI2050 conditions with present land use, and after including autonomous land use changes

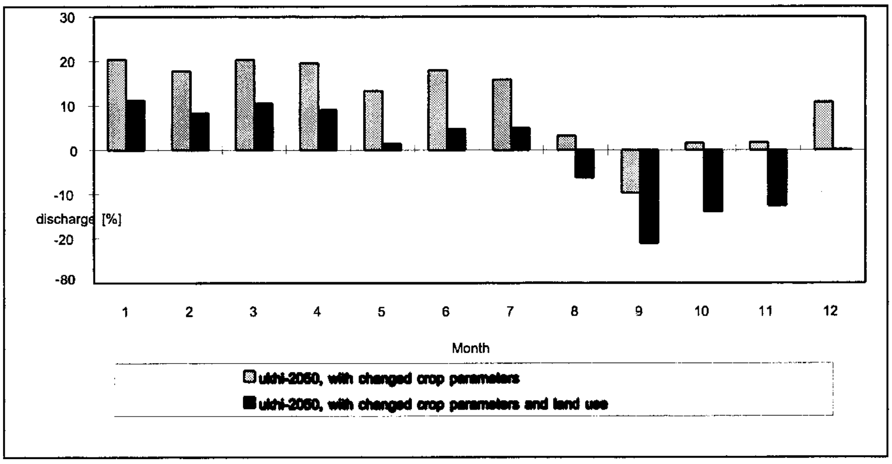


Figure 13.2. Changes in monthly discharge under UKHI2050 conditions with present land use, and after including autonomous land use changes

influence on crop production. However, the implications of a climate change as assumed in this study are minor for land use, compared to the influence of autonomous changes. In general, also without climate change, it may be expected that the area of built-up land will increase but the agricultural area will decrease at a faster rate. This may offer possibilities for nature development and afforestation.

The anticipated land use changes according to the evaluated scenario will lead to increased interception and evapotranspiration, resulting from an increase in the area of forests. As a result, river discharges in the lowland part of the Rhine basin may decrease by about 10%. This reduces the increase in winter discharge that is due to changed climate conditions, but, on the other hand, further reduces discharge during late summer.

14 Impacts of hydrological changes in selected sectors and regions

This chapter describes derived impacts of climate changes in selected sectors. Some of these derived impacts can be described only in a qualitative manner. In addition to simulation uncertainties, difficulties to access vital data for this kind of assessment is the major reason for not being able to give more quantitative facts on the impact side at this stage. With regard to public interest, economic effects and the diversity of impacts as a consequence of regional diversity, the selected impact sectors are shown in table 14.1 below.

It can be stated here that all water resources management systems have a built-in degree of flexibility to adapt to changing conditions on a short-term basis as e.g. in the event of floods or chemical spills into rivers and the protection of water quality for supply purposes. The impacts described below are general in character and decision-makers should use the identified impacts to undertake in-depth analysis of systems' flexibility in view of a perceived climate change and changing hydrological conditions. However, besides the short-term response flexibility of water resources management systems, there are adaptations necessary with a long-term perspective and high associated costs.

Amongst them are adaptations of inland navigation with respect to the maintenance of the depth and width of the shipping channel during the expectedly more pronounced low flow conditions with the time horizon of the year 2050. Also associated are the reaction of shipping agents and a possible shift of mass transport to roads and railways and – as a chain reaction – resulting ecological impacts which have not been assessed in the scope of this study. Winter tourism in the Alps is another long-term impact, with a high economic impact and risk potential which is described in detail below. Some of the expected socio-economic implications of hydrological changes have already been discussed in chapter 3 of this study and policy recommendations are outlined in chapter 15.

14.1 Inland Navigation on the Rhine river

14.1.1 German part of the Rhine

The greatest freight traffic intensity on the Rhine river is observed on the reach between Rotterdam and Duisburg/Ruhrort. It decreases step by step when passing Koblenz, Mannheim-Ludwigshafen, Strasbourg, Breisach and Basel. Respective values for the year 1991 can be retrieved from figure 14.1.1.1. To increase the reliability of inland navigation, great efforts are undertaken. In the first place, adequate and reliable forecasts may help to optimise loading the ships during periods of low flow. These may also help to announce the times to stop and restart navigation during floods. In addition, works are carried out to improve the river channel's function as a water way for navigation.

Table 14.1 Scale levels of selected impacts

Impact Sector	Regional Scale	Time Scale
Inland navigation	All, except alpine and pre-alpine region	Days (flood events, low flow spells), Seasonal
Power generation	Alpine, pre-alpine and middle part of the Rhine basin	Seasonal
Water Supply (Cooling)	All regions, pronounced in smaller subbasins	Seasonal
Water Quality	All regions, pronounced in subbasins of the Rhine	Not fully studied! Seasonal, possibly persistent for certain pollutants
Floods	All regions	Hours - Days
Winter tourism	Alpine areas	Seasonal

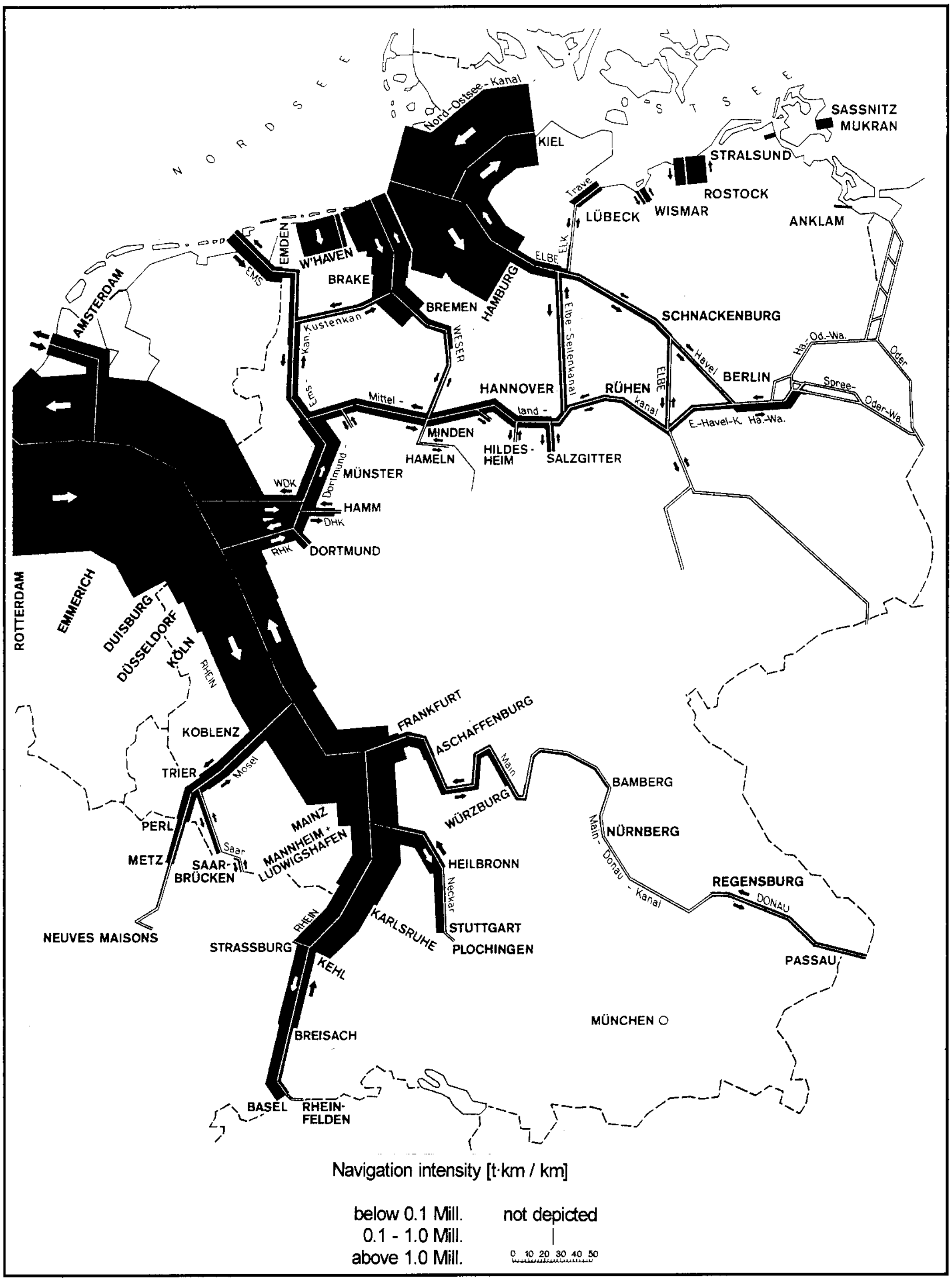


Figure 14.1.1.1 Waterways in Germany and respective navigation intensity (1991)

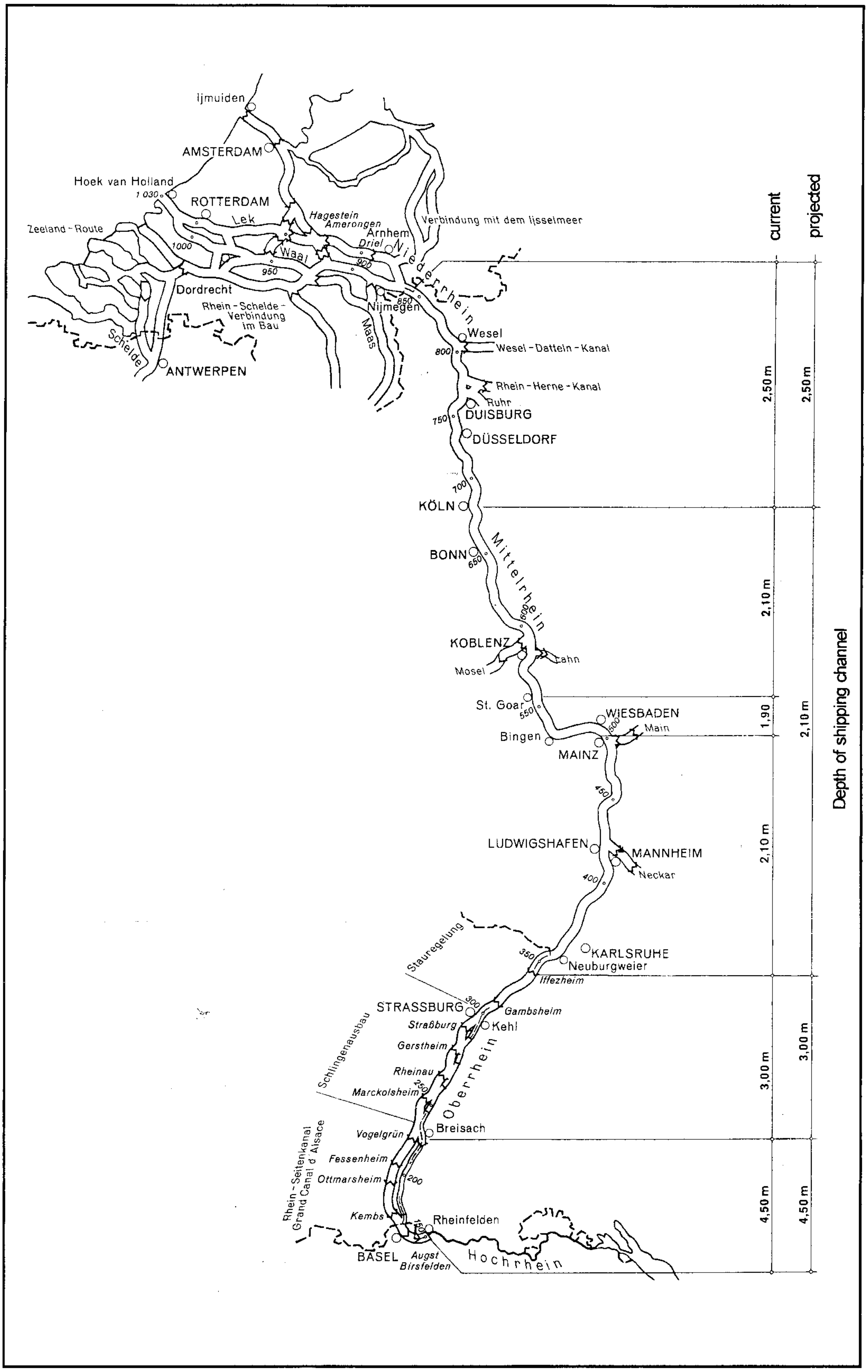


Figure 14.1.1.2 River Rhine downstreams of Basel and depth of shipping channel (1991)

During low flow conditions, especially the middle reach of the Rhine, which presently acts as a bottle-neck is affected. In figure 14.1.1.2 the depth of the navigation channel along the Rhine is indicated. These levels are the low flow water levels critical for navigation. Currently, at this reach, the depth of the river channel is increased from 1.9 m to 2.1 m. On the average, water level drops below it during 20 days per year. In addition, during extreme floods, navigation is not possible in the narrow most sections in this stretch.

Scenario calculations indicate that in winter time, a higher flooding frequency may be expected, resulting in an increase of the number of days that are lost for navigation. During the summer period, low flow situations will become more tight. The runoff reduction during summer may on the long run require a further deepening of the river channel of the middle Rhine reach.

14.1.2 Inland navigation in the Netherlands

Transport companies choose between various types of transport such as aircraft, shipping, railways or roads to transit their goods. The choice between these types depends on the type of goods, on transport costs, time and reliability. In Western Europe navigation on the Rhine river provides for a large exchange of goods between industrial centres of the Rotterdam harbours and of the Ruhr area in Germany. In the year 1989, 267 millions of tonnes were transported on the Netherlands Rhine branches. Waterborne transport over the Rhine river is reliable since discharge in the main river branches is sufficient to allow for easy navigation during most time of the year. Ships travel slowly, but for many types of goods the costs are relatively low since ships can carry large volumes of cargo. From an environmentalist's viewpoint this type of transport is preferable above other types since it uses less energy and produces less pollutants.

It is for these reasons that transport organisations and water management authorities expect increased waterborne transport on the Rhine in the coming decades. Exact forecasts are difficult to produce since the expectations vary much depending on long-term economical growth. Instead of making forecasts, various scenarios are developed, based on different economic growth rates. These scenarios also include possible shifts from one type of transport to other types.

These long-term expectations however do not include any analysis of effects of possible changes in river regime due to environmental changes. A climatic change that would lead to prolonged droughts would inevitably lead to lower water depths during the dry season which in turn would probably hamper navigation. On the other hand, if the climate changes were to lead to increased precipitation during the dry season this could very well facilitate navigation in these periods. Both changes may have consequences for the choice of the means of transport.

These considerations led to the aim of this chapter which is to make an initial assessment of the impact of discharge changes on navigability during the coming decades, between the Rotterdam harbours and the Ruhr area. The study is limited to an analysis of climate induced changes in river regime against the long-term needs of shipping with respect to water depth and channel width. The chapter forms an abstract from four reports that have been recently published by the Rotterdam Harbour Company (Timmermans, 1995; Geenhuizen *et al*, 1996; Nomden, 1996; Snijders, 1996)

Conditions required for navigation

The expectations that waterborne transport on the Rhine river will increase in the coming decades have led to a series of targets, in terms of depth and width of the channel, defined by the water management authorities (Rijkswaterstaat). These targets are related to the safety and facility of navigation, as well as to the transport capacity of the navigation traffic (RWS, 1993). If water depth is reduced, ships can carry less cargo and transport costs will rise. Width of the channel is related to ease of navigation. Particularly in river bends a narrow channel will hinder the passing of ships when traffic is heavy. In the Netherlands, the most important river branch for waterborne transport is the Waal branch. Optimal transport along this branch would mean that the presentday safety and facility of navigation

Table 14.1.2 Changes in flow durations according to the different climate scenarios
Expected flow durations in days per year

	< 500 m³/s	<1000m³/s	2000-5500m³/s	Period that barge combinations can travel up the river (%/year)
present	0	19	168	46
ukhi2020	0	29	164	45
ukhi2050	0	34	156	43
ukhi2100	1	48	148	40
xccc2020	0	24	170	47
xccc2050	0	26	170	46
xccc2100	0	29	166	45

is maintained, that the water depth in the channel should be at least 3 meters and that the width of the channel should be at least 170m. This is referred to as OLR 3.0. The minimum requirement is a channel depth of 2.5m and a channel width of 150m, this is referred to as OLR 2.5. There is an international agreement that this last level should be exceeded at 95% of the time. Translation of the minimum level into discharges at the Lobith monitoring station means that the Rhine river discharge should exceed 984 m3/sec at 95% of the time. These OLR 3.0 and 2.5 are targets that are designed to facilitate easy navigation for the majority of the vessels sailing up the rivers. However, in terms of tonnage most of the cargo is transported by large barges that are pushed. Navigation with these large pushed combinations is restricted to periods when the discharge at Lobith gauging station is between 2000 m³/sec and 5500 m³/sec.

Results

The expected average monthly discharge changes were translated into changes in duration of average and low flows. Therefore a method for estimating the effect of climate changes on future recurrence intervals and duration times of discharge peaks of the Rhine in the Netherlands was developed by Kwadijk and Middelkoop (1994). The method is based on the relationship between average monthly discharges, frequencies of occurrences of peak discharges and peak flow duration times. Asselman (1997) extended this relationship to low flow periods.

Here we focus on changes in duration of discharges that affect navigation. As mentioned in earlier paragraphs, navigation is severely hindered when the Rhine discharge at Lobith gauging station falls below 1000 m³/sec. At a discharge below 500m³/sec, navigation is only possible for recreational purposes. The large barge combinations can only sail up the river if the discharge is between 2000 m³/sec and 5500 m³/sec.

Table 14.1.2 suggests that the period during which the ships can travel without load reduction (more than 1000 m³/s) will shorten. According to both the UKHI and the XCCC scenario, this trend will already become apparent in the next few decades. However the UKHI scenarios envisage a greater reduction during the successive decades after 2020 than the XCCC scenarios.

In contrast, the period that the large carriers can travel up the river will not be affected according to the XCCC scenarios. The UKHI scenarios also suggest only a relatively small reduction. The reason for this is not only that periods of small discharge will become longer but so too will those of large discharge, both at the expense of the period of average flows.

Conclusions

In this tentative assessment, all scenarios envisage longer periods with hampered navigation. However, different scenarios suggest different changes in the period that low flows will occur. This trend may already become apparent in the coming decades. The results also suggest that transport with smaller carriers will be more affected than transport using the larger barge combinations. With respect to the long term targets for inland navigation referred to as OLR 3.0 it can be concluded that these targets can only be reached with much more effort than is required under the present day river regime.

Ongoing research

Ongoing research into the effects of climatic change on inland water transport also includes possible measures to reduce the most undesirable effects. An item now under study is the possibility of using the lakes in the Alpine region to regulate the Rhine discharge. These lakes at present are mainly used for hydropower generation, this may lead to conflicts between the needs of the power generation and the needs of the inland water transport.

As the vessels travelling up the Rhine river differ in length, width and draught, easy navigation with these various vessels will therefore require varying river channel dimensions. As the depreciation time of the vessels is within the same order as the expectations around climate change, possible changes in river regime as a result of climatic change should be considered in the design of new ships. Design of ships also affects the design of terminals that are used to trans ship cargo. This research also aims to identify the vessel type least affected by changes in river regime.

A last item is research into the measures and decisions taken by shipping companies to maintain their transport under present low flow conditions. This present day management is evaluated with respect to the possible changes in river regime.

14.2 Hydropower generation in Switzerland

In all climate scenarios, the yearly discharges in the Swiss basins are decreasing under the climate change conditions, most of them presenting a rise in the winter months. The decrease for the 2050 conditions amounts to approx. 40 to 60 mm per year, which represents some 10 to 15 percent. This means an overall decrease of hydropower production for the power stations at the rivers which also amounts to an average 10 to 15 percent over a number of years. The decrease will be of particular importance during the summer season whereas in winter months a rise is predicted.

The effect of these changes is at least partly compensated by the fact that power consumption is more important during winter and less so during summer. Therefore the economic loss need not be proportional to the decrease in river discharge. Due to the more even regime, with less important flood events during summer and higher water stages during winter, the overall losses due to discharge of water over spillways will be less significant then today.

With regard to the reservoirs in the Alps in which water is stored during summer in order to produce electric energy in the winter months, it is almost impossible to predict the consequences of climate change. Much depends on the altitude of the hydrological basin of the reservoir, and of the distribution of precipitation among the seasons. It also depends on the time when the reservoir is filled up or is emptied. However, the management of these reservoirs is not only dependent on the hydrological conditions in their hydrological basins. The economic conditions on the electricity market – the price of electricity in the international market – plays at least an equivalent role.

In conclusion we can say that the climate change scenarios lead to a decrease of the overall production of hydropower. On the other hand, the hydropower production will be better distributed over the season, e.g. more hydropower will be available in wintertime.

14.3 Water supply

Many results from the scenario model runs indicate that the water resources for water supply will diminish:

- Increased evapotranspiration will diminish soil humidity and ground water recharge.
- Low flow will be more important with lower stages and more low flow days in summer season in small- and medium-scale catchments. This is true for prealpine and midland catchments. It is not true in Alpine catchments with still important amounts of snow

melt in spring and summer. Here low flow – that occurs in winter – will increase.

- Low flow in larger rivers of the lower Rhine basin will further decrease in summer and autumn.

These consequences of climate change on hydrology will be followed by reactions in certain aspects of water resources management:

- Demand for *irrigation water* for agriculture will increase. This demand will be most important during the periods of low flow. Often irrigation water is taken from the rivers, where in climate change conditions low flows will be more important. Conflicts with the quantitative water protection regulations (residual waters) may therefore occur more frequently.
- An important amount of *drinking water* is taken from ground water. Due to increasing drinking water demand and due to diminishing ground water recharge, measures have to be taken to find other drinking water sources or to economise the use of drinking water.
- Industry and mainly thermal power plants have large demands for *cooling water*. Today, water is taken from larger rivers and – warmed up – recharged back to them. In Switzerland, water protection regulations stipulate that
  - recharged water must not exceed 30°C;
  - river water should not be warmed up by more than 3 degrees and
  - the maximum temperature in the river should not exceed 25°C. These conditions are valid down to the 0.05 percentile of river runoff.

Under climate change conditions water temperature will increase parallel to changes of the air temperature (see chapter 14.4). With decreasing runoff this effect may even be strengthened. Therefore, there may be periods in summer or autumn when the legal regulations could not longer be kept due to increased low flow and at the same time increased water temperature. Consequences would be to slow down or to stop industrial and thermal power plants during severe low flow periods.

14.4 Water quality – water temperatures in Switzerland

The evaluation of temperature measurements in rivers since the middle of the century shows that meteorological and hydrological factors such as radiation and heat exchange influence water temperature. Other factors have also been involved, including anthropological influences: significant amounts of cooling water demand, alpine reservoirs for hydropower stations and climate changes. The analyses of the time series (Jakob et al., 1996) show an increase of water temperature in the larger Swiss rivers of more than 2 degrees since the 1950s (see figure 14.4.1.1). This increase corresponds well with observations of water temperature in the Rhine river at the German/Dutch border in Bimmen/Lobith. In the same time period, an increase of approx. 1 degree in air temperature was observed.

When comparing time series of air and water temperature, it can be concluded that approx. 1 degree of water temperature increase is due to the effect of cooling water from nuclear power plants and of waste water input in the river system. This shows that water temperature is increasing quite proportionally to the increase in air temperature.

This means that a further increase in air temperature with a climate change scenario will lead to a proportional temperature increase in waters. Together with an increase of low flow situations in the warmer season (see chapter 11.1), it must be assumed that higher temperatures in Swiss water will be observed more frequently. By now maximum daily values are already rising sometimes above the legally set limit of 25 degrees C. It must be assumed, that in climate change conditions this limit will be passed much more frequently. This limit is legally set in order to avoid damages and losses in aquatic biology and a decrease in water quality. Cooling water may therefore not be fed back into the river if this limit of 25 degrees would be exceeded. On top of this, the water temperature of a river may not be increased by more than 3 degrees.

Water temperature is strongly linked to water quality and is a significant factor for the composition of aquatic biomass. Effects of a

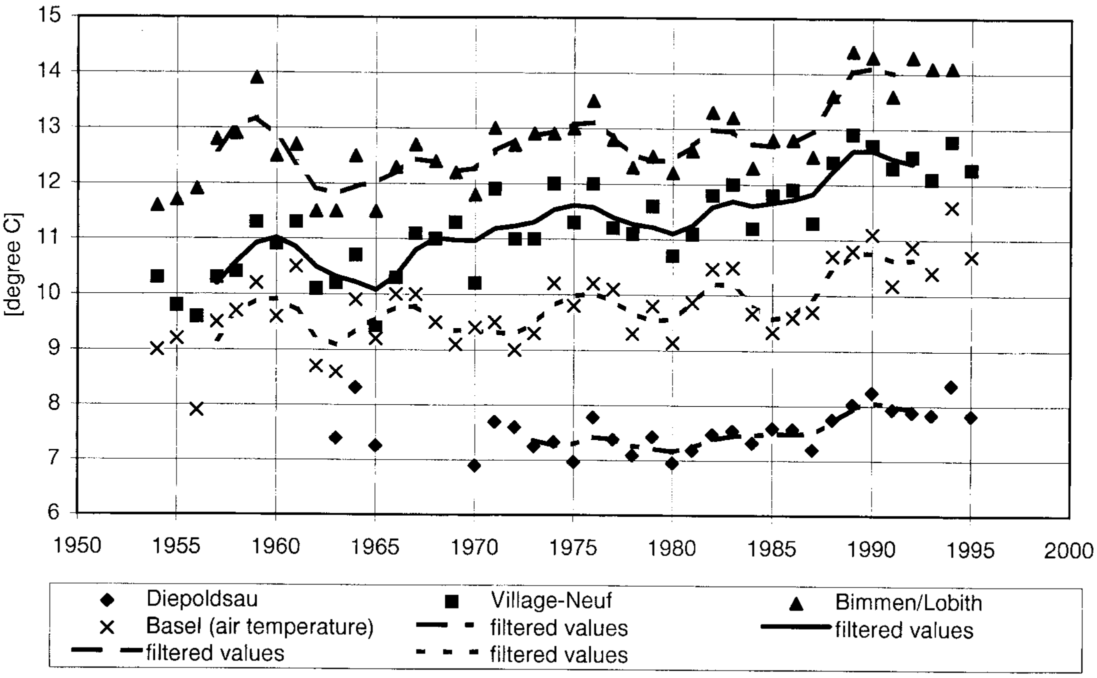


Figure 14.4.1.1 Temperature development in the Rhine river above Lake Constance (Diepoldsau), in the region of Basel (Village-Neuf) and in Bimmen/Lobith (lower Rhine) compared to air temperature in Basle. Values are filtered with a Gaussian low pass filter over time periods of 7 years. (figure from Jakob et. al., 1996)

further water temperature rise on aquatic biology cannot be neglected. For example, it is well known that the best habitat temperature for brown trout is around 8 to 17 degrees C. If the temperature exceeds 18 degrees, the trout becomes stressed due to the decreasing oxygen dissolved in the water. Water temperatures above 24 degrees are lethal. This means that this species will migrate from its actual habitats to cooler environments and other species will follow from places further downstream.

Water quality may not only decrease due to water temperature increase but also due to the more frequent low flow situations. During these periods waste water may not be sufficiently diluted by the river water and hence the legal concentration limits cannot be fulfilled.

14.5 Floods

14.5.1 Alpine rivers

Under climate change conditions, the frequency of floods is changing in the transition zone of the pre-alpine – alpine region of the northern Alps, which is an important part of the upper Rhine:

- Less summer precipitation in combination with higher evapotranspiration values causes decreasing soil moisture and less groundwater recharge. Consequently summer floods are decreasing slightly. This is true under the assumption that the precipitation intensity will not change significantly in summer season.
- On the other hand, higher winter precipitation in combination with a rising zero degree level will cause substantial rises in winter peak flows.
- Annual peak flow will not change significantly for small return periods, but for return periods of 50 years the increase may exceed 10 %. However, this increase is still within the statistical uncertainty bounds of around 30 %.

Consequently, flood protection measures must be reinforced. The principal objective – to protect human lives and objects of value against the damaging effects caused by water – is to be achieved with a minimum of interference with the water courses. In Switzerland, the following legally stipulated order of priority must be observed:

- proper maintenance of water courses
- land use planning measures
- structural measures for the protection of water courses.

Proper maintenance of water courses
'Proper maintenance of water courses' refers to the maintenance of flow capacity and of the effectiveness of structural protection measures. This includes the removal of bushes and trees which restrict the flow-through profile and endanger the stability of correction structures, the removal of driftwood from the area affected by floods, the removal of dangerous colmations, the emptying of sediment retention basins, and the repair of minor damage to protective structures. When such maintenance tasks are carried out, the interests of environmental protection and fishing aspects must be taken into account. Proper maintenance is a permanent task. In spite of careful maintenance, the service life of certain protective constructions is limited. By carrying out periodical examinations of the conditions of the protective measures taken, it is often possible to detect any weak points before damage can be caused.

Land use planning measures
An increase in the damage potential can be limited or even prevented through the avoidance of endangered areas and the implementation of legislation (e.g. refusal of building permits in greatly endangered areas, measures for the protection of buildings, regulations governing agricultural utilisation, etc.). This should also include aspects relating to economics (balance of interests). The regional authorities are required to compile risk registers and maps depicting endangered areas and to take these into account in their guideline and utilisation planning. In principle, no subsidies can be granted for measures aimed at the protection of buildings and installations which will be erected in designated danger zones or known risk areas.

Structural protection measures for water courses

As a result of the intensive building development over the past few decades and the accompanying increased utilisation, protection deficits have arisen at many locations which can no longer be rectified by means of maintenance and planning measures. For this reason, structural protection measures will continue to be required for water courses in the future. The planning of such measures calls for knowledge of the possible natural processes and their influences. The measures should be carried out in a way that is as close to nature as possible and avoids interference with the landscape. Emergency interventions following damage that has occurred should not run contrary to these principles in the long term.

14.5.2 German part of the Rhine

Floods within the River Prüm catchment

Damages due to flooding occur downstream of the town of Prüm, which is located in the upper catchment area. Factories, campsites and public swimming facilities are mainly affected. The town of Irrel near the mouth of the Prüm river is regularly affected to a major degree. Even a 5 year flood will affect 30 houses. Technical flood protection could be useful for this area. An engineering office is carrying out preliminary investigation into this.

The application of the climate scenarios indicates no major changes with respect to flood risk in general. Daily maximum flows are of the same magnitude as the control run, though the flow exceeded in 5% of the days has decreased slightly, indicating a reduction in flood frequencies. It must be mentioned that in this study area, damaging floods are mainly caused by consecutive days of precipitation. Changes in weather conditions can have an even larger effect on flood situations than changes in precipitation amount and intensities. This study does not take into account any changes in the number of rain days, so that the interpretation of results with respect to floods must be done very carefully.

Additionally, the influence of temperature on the precipitation form will cause altered flood conditions. The number of floods due to snow melt and succeeding rainfall will be reduced. On the other hand, flood events that were curtailed due to intrusion of cold air masses and snowfall instead of rain under present climate conditions will become more frequent. Due to the coarse resolution of the climate scenarios, these effects are difficult to estimate. They concern also changes in convective weather conditions which are significantly related, especially to the occurrence of summer flood events in small catchments such as the Prüm.

Adding this to the general simulation results, it can be assumed that damages due to floods will be of the same magnitude as present. As mentioned before, technical flood protection is already in the state of planning and, after realisation, will reduce damages with respect to both present as well as forecast changed climate conditions.

Floods within the River Blies catchment

Even minor flood events can cause damage to all settlements along the Blies river, from the spring to its confluence with the Saar river. Close to the source the town of St. Wendel, located downstream of the confluence of the Todtbach and the Blies, is affected, as are houses and factories in Ottweiler and Neunkirchen. Downstream of the confluence of the Schwarzbach and the Blies, the old part of Blieskastel is flooded by a 20 year flood event. Up to the confluence of the Saar, the floodplains of the Blies can be 500 m wide, affecting houses and farms in particular.

The planning of a retention basin near the town of Ottweiler-Ziegelhütte is in progress, a preliminary scetch has been prepared. This retention basin is supposed to prevent damage caused by 20 to 30 year floods. The December 1993 flood was a 100 year flood with reference to Blieskastel. Floods of such an extent still endanger the basis of livelihoods.

The application of the climate scenarios indicates no major changes with respect to flood conditions. The maximum daily flows indicated by the scenario runs range from 10 percent below to 10 percent above the maximum flow of the reference situation, but all scenarios also indicate a slight reduction of flood frequencies. As in the Prüm catchment, the same uncertainty regarding the changes in precipitation form and the resulting consequences on floods can be assumed for the Blies catchment. Accordingly, it can be concluded that flood damage indicated by the scenarios will be within the present range. Even though it will not be possible to avoid all damage caused by extreme floods, measures against floods, like the retarding basins already planned will reduce losses due to minor floods.

Floods of the Rhine river

The discharge of the Lower Rhine is governed by glacial and nival regimes with an obvious maximum in summer and a minimum in winter. On all tributaries of the Rhine river originating in the medium relief mountains, the pluvial regime prevails, with lower discharges in summer and higher discharges in winter. In figure 14.5.2.1 this influence is to be seen at the Worms gauging station, downstream at the mouth of the Neckar river, Kaub, downstream at the mouth of the Main river, and especially at the Andernach gauging station, downstream at the mouth of the Mosel river. Within the total Lower Rhine area, the discharge maximum remains in winter.

The scenario calculations show, that the runoff regime of the Rhine river will change substantially, due to the replacement of the nival regime by the pluvial regime. Thus the discharge is rising in winter and is decreasing in relation to the present state within the total Rhine basin. The runoff regime in the medium relief mountains is currently dominated in winter months by a sequence of snow fall, growing and melting of the snow cover, and rainfall. Due to the expected increase in temperature and in atmospheric circulation, this sequence will be reduced in time, i.e., the rainfall fronts will follow each other at increased frequency, and the duration of intrusions of warm and cold air masses will be shorter. At the increased temperature, the proportion of precipitation falling as rain and accounting for areal precipitation will rise equally.

With regard to the generation of floods, the effects are different. Floods generated by rain and simultaneous snow melt and frozen top soil will be observed to a lesser extent. However,

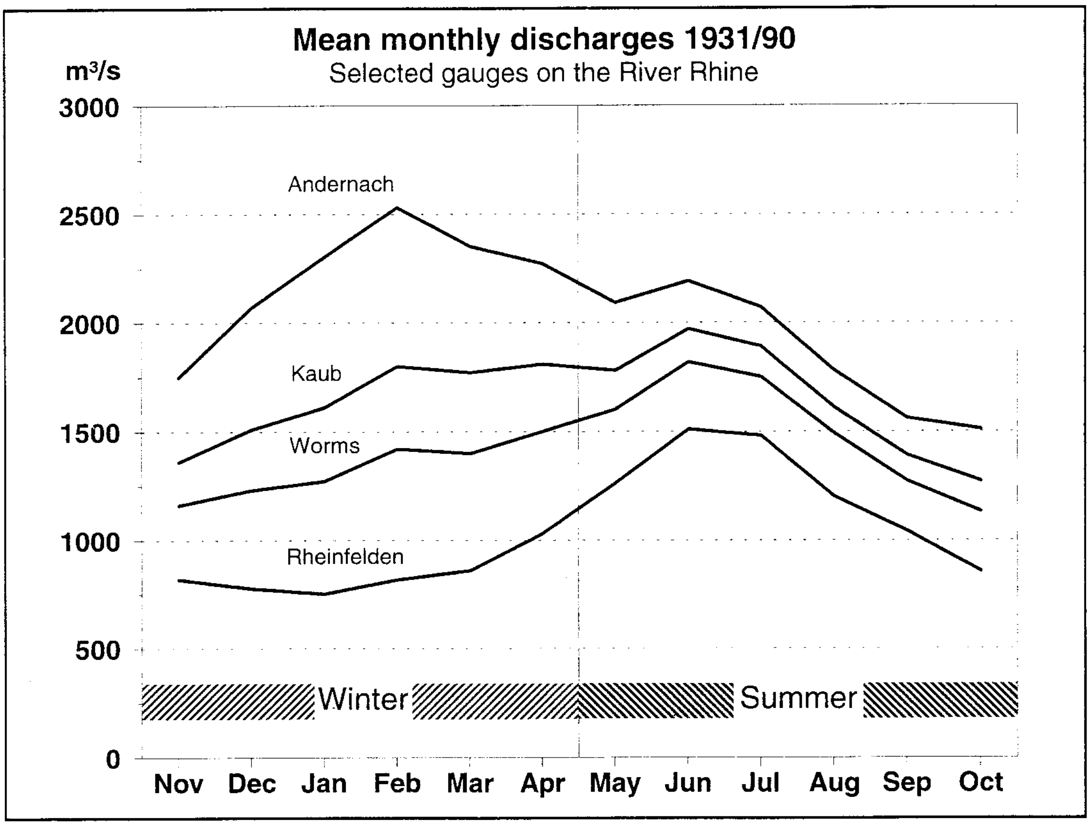


Figure 14.5.2.1 Rhine runoff regimes

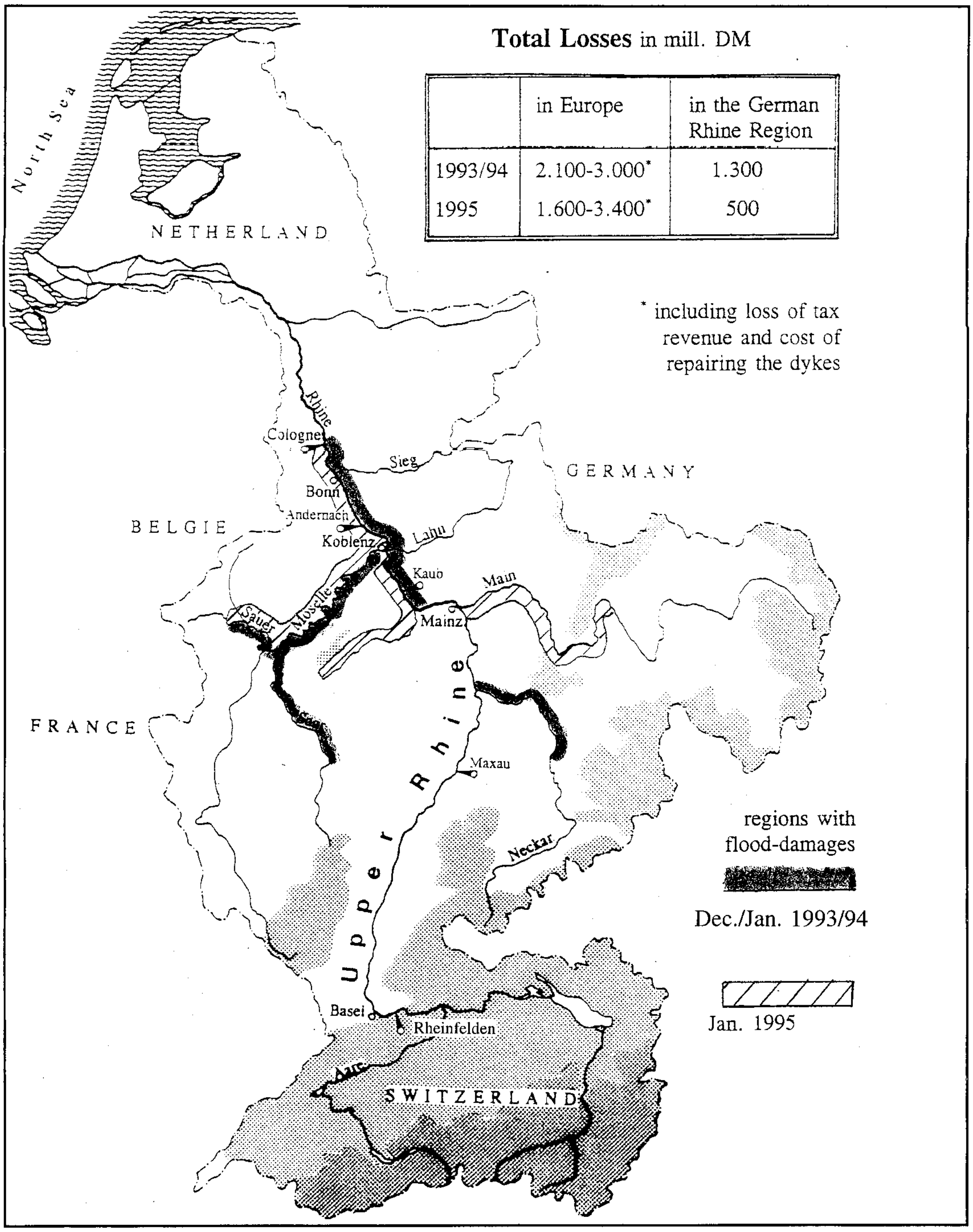
floods generated by rain only, will occur more frequently. Many of these floods were stopped at a critical phase in the past by intrusion of cold air masses, leading to precipitation falling as snow and to storage of water masses on the land surface at that time, resulting in runoff only at a later stage, when the overall flood imminence was past. In general, when working on the basis of these thoughts, an increase of the general flood risk in winter has to be accounted for. During summer, equally local floods may occur more often, generated by more frequent convective, high intensity precipitation.

As the scenarios do not permit any statement on the change in precipitation intensity, the question of increased frequency and/or extents of extreme floods remains unanswered. Nevertheless, there is a risk that the total catchment of the Rhine river from the Upper Rhine to the Lower Rhine may contribute in the same manner to flood runoff, thus resulting in an extreme flood of a kind which could not occur as a result of the various runoff regimes encountered until now.

At the 11th conference of the Rhine ministers, the decision was made to add runoff related issues to the tasks of the International Commission for the protection of the Rhine river (IKSR, see IKSR, 1997a). Under the impression of the extreme floods during January 1995, the Ministers for Environmental Protection of the European Union responsible for the Rhine and Meuse rivers engaged the IKSR to develop a 'Flood' action plan for the International Rhine basin, with the consent of Switzerland.

As a first step, the basic outlines and the strategy of the action plan have been worked out. An additional task was the analysis of the present flood protection facilities as well as already existing concepts for improvements. In detail, the inventory gives information about:

- existing problems related to floods,
- state of existing flood protection and its effect, damaging potential, activities,
- existing concepts including their objectives, costs and duration of realisation,
- flooded areas along the Rhine river and its tributaries,



Total Losses in mill. DM

	in Europe	in the German Rhine Region
1993/94	2.100-3.000*	1.300
1995	1.600-3.400*	500

* including loss of tax revenue and cost of repairing the dykes

Figure 14.5.2.2 Regions with flood damages within the German portion of the Rhine basin during the 1993/94 and 1995 floods, with respect to the federal waterways

- legal basis for flood protection with respect to the riparian countries,
- national strategies to improve flood protection as well as flood forecasts.

The analysis does not include statements concerning climate changes. Even with respect to this however, the objectives declared by the IKSR must be tackled intensively: the first aim is to stop man-made amplification of floods and to reduce existing restrictions. Furthermore, the increase of the damaging potential must be limited and, as far as possible, the existing damaging potential has to be reduced. In order to protect historically developed settlements from the remaining damage potential, technical flood protection is indispensable.

The degree of the existing flood protection along the Rhine river varies. The main objective of the action plan is to come to the state of a commonly accepted responsibility regarding the protection objectives, and the integration of local boundary conditions. The inventory and the documentation of the 'basis and strategy of the action 'Flood' plan are the starting points for the further activities required, that will be outlined precisely within the action plan of the IKSR.

In taking precautions against floods, timely warning is important. The population must be able to protect both human life and possessions in case a flood is imminent. Long-term forecasts with high reliability are needed because additional time available will reduce the damage suffered (IKSR, 1997b). Additionally, the awareness of the endangered population has to be improved and must be updated from time to time. On the other hand, the citizens are also responsible and can also contribute to the reduction of losses. This can be seen by comparing the estimated losses of the 1993/94 and 1995 floods. In fig. 14.5.2.2 the regions suffering damage due to the floods in 1993/94 and 1995 are outlined, concerning only river stretches of the federal waterways. The estimated total losses in the German Rhine Region were 1,300 mill. DM in 1993/94 and 500 mill. DM in 1995, respectively.

For the city of Cologne as an example, the losses due to the 1993 flood were nearly halved in 1995 although both floods were comparable in magnitude. Besides the awareness of the population, damages were reduced by a slower rise of water levels in combination with quite precise forecasts of water levels and the time of peak flows.

As an important conclusion it must be mentioned that there is no linear relation between maximum water levels and losses. Each flood has its own characteristics, and the sensitisation of the population can have a large influence with respect to the losses. Integrated action as outlined in the action plan of the IKSR will be necessary to reduce losses due to flooding as far as possible.

14.5.3 Floods, safety and flood damage in the lowland part of the Rhine basin

Lower Rhine

In the Netherlands the safety level of the river dikes that protect the inland areas from river flooding is based on a failure probability of 1/1250 per annum. The accompanying design discharge is calculated on the basis of the discharges that occurred over the past century. If a climate change leads to an increase of discharge of the Rhine during the winter period, the probability of extreme discharge peaks and hence of the design discharge will increase as well. From the available data and due to statistical uncertainties, it is not possible to give precise estimates of the increase of the design discharge. The results obtained so far indicate that the design discharge of the Rhine river in the Netherlands may increase in the order of about 5 to 8% by the year 2050. The overall results suggest that an increase of 10% should be accounted for by the year 2100.

Overijsselsche Vecht

A time step of only one day was used for the lowland model. This allows the estimation of probabilities of peak flows by means of statistical analysis and extrapolation of the annual peak flows calculated by the model for different climate scenarios. The results are given in figures 14.5.1 and 14.5.2. For this purpose, Gumbel distributions were fitted on the frequency distribution of the annual maxima. The results were extrapolated to a recurrence time of 1250 years. In the Netherlands, design discharges for the construction of river dikes are derived from this recurrence time. The results indicate that according to the UKHI scenario the design discharge may increase by about 25% by the year 2050. The XCCC scenario shows more moderate increases of peak flows.

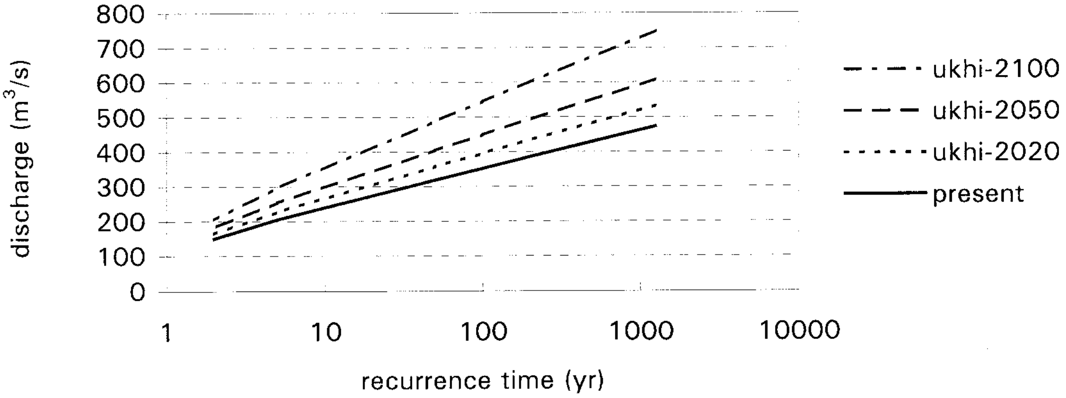


Figure 14.5.1 Changes in recurrence time of peak flowsd of the Vecht according to the UKHI scenario

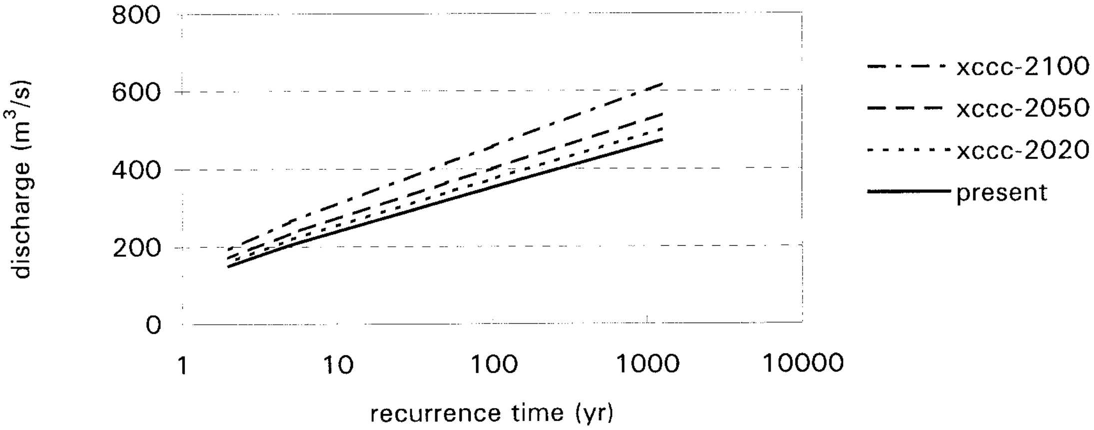


Figure 14.5.2 Changes in recurrence time of peak flows of the Vecht according to the XCCC scenario

14.6 Winter tourism in the Alpine region

In mountainous regions, winter tourism activities during winter depend strongly on the thickness of the snow cover and on its period of availability. The most important period for skiing activities starts on 16th December and ends on 15th April, after which date most of the ski resorts are closed. The Abegg study (1996) established that the profitability of the winter sport resorts requires a minimum of 100 days during this period (containing 121 days) with an adequate snow layer. The minimum required water equivalent of the snow cover is approximately 50 mm for the activities related to cross-country skiing and 100 mm for Alpine skiing.

Altitude slices adopted in the snow simulation of the IRMB model allow the study of the altitudes higher than 900 m and lower than 1500 m. For the three catchments, the 900-1200 m range can be examined. The 1200-1500 m range can only be tackled in the case of the Broye catchment. In the Murg catchment, 1 percent of the basin area (2 km^2) is included between 900 and 1035 m; in the Ergolz 3.1 percent (8 km^2) is between 900 and 1169 m. In the Broye catchment 3.7 percent (14.5 km^2) is in that range while 1.4 percent (5.5 km^2) is between 1200 and 1500 m.

Adopting the above-mentioned thresholds in order to investigate the profitability of the skiing activities in the three catchments, table 14.6.1 has been constructed. It is clear that even under the present climate conditions the Ergolz and the Murg catchments are not in a favourable region with regard to ski investments. On average, only five weeks are available for these activities in the Murg catchment and only two in

Table 14.6.1 Number of days during the winter tourism period (16/12 to 15/4) on which the water equivalent of the snow cover is greater than the 50 mm and 100 mm thresholds under present conditions

winter tourism season	1981-82	1982 83	1983-84	1984-85	1985-86	1986-87	1987-88	1988-89	1989-90	1990-1 91	1991-92	1992-93	mean
Number of winter tourism days during which the water equivalent of the snow cover is greater than 50 mm													
Altitude range: 900-1200 m													
Broye	121.0	85.0	98.0	121.0	109.0	120.0	69.0	76.0	10.0	58.0	97.0	41.0	83.8
Ergolz			69.0	23.0	29.0	4.0	26.0	0	0	13.0	0	7.0	17.1
Murg	121.0	15.0	83.0	96.0	36.0	19.0	38.0	0	0	14.0	14.0	0	36.3
Altitude range: 1200-1500 m													
Broye	121.0	121.0	117.0	121.0	112.0	121.0	106.0	121.0	72.0	121.0	122.0	121.0	114.7
Number of winter tourism days during which the water equivalent of the snow cover is greater than 100 mm													
Altitude range: 12001500 m													
Broye	121.0	118.0	100.0	113.0	109.0	119.0	86.0	121.0	63.0	121.0	117.0	121.0	109.1

the Ergolz catchment. In fact, only very small mobile ski lifts for children are occasionally in operation in these two regions. Between 900 and 1200 m, the Broye catchment has some 84 days with enough snow for cross-country skiing. The year-to-year variability is very important for the three catchments. During the 1989-90 winter season, very few favourable conditions were met, as was also the case during the 1992-93 season.

In the higher altitude slice of the Broye catchment, the 100 days required per season are obtained, confirm existing resorts. As the snow cover is very important here, the variability is not so large. The worst season for cross-country skiing was the 1989-90 winter with 72 days, and 63 days for alpine skiing.

The outline of the impact of the climate scenarios on snow tourism potential is presented in table 14.6.2. The decrease in the number of skiing days is significant in the 900-1200 m range. In most of the scenarios, less than 20 cross-country skiing days are simulated for the Ergolz and Murg catchments. For the Broye catchment, more than 60 days will remain in 2020, but less than 30 in 2050. In the upper part of the Broye catchment, more than 100 cross-country skiing days are still forecast for 2020. In 2050, depending on the experiment 80 to 90 days are assessed. There is great uncertainty for the more distant future as the UKHI2100 produces only 34 cross-country skiing days whereas the XCCC2100 gives around 92 days.

Due to the small amount of snow simulated in the Ergolz and the Murg catchments, the alpine skiing potential has only been tackled in the Broye catchment. Under present conditions, some 109 days per winter season are simulated in the 1200-1500 m altitude range while only 60 days are found in the 900-1200 m ranges. Under the GC conditions, sensitivity equal to that of the cross-country skiing activities has been yielded in the higher altitude range. In 2020 some 84 to 96 days are good for Alpine skiing, meaning a fall in the profitability of winter sport resorts. In 2050, 65 to 87 will remain. Obviously, alpine skiing activities are worse hit by the rise in temperature than the cross-country skiing activities. Although the cross-country skiing potential is still unmodified in 2020 scenarios, the alpine skiing potential has already been subject to significant depletion. The decrease is dramatic in the lower altitude range.

In higher altitudes, the decrease in the number of days with sufficient snow cover for tourism is in the same order of magnitude. Nev-

Table 14.6.2 Mean number of days during the winter tourism period (16/12 to 15/4) on which the water equivalent of the snow cover is greater than the 50 mm and 100 mm thresholds under present conditions, and in the stationary UKHI and CCC experiments and the UKTR transient experiment

Scenarios	Present	ukhi2020	ukhi2050	ukhi2100	xccc2020	xccc2050	xccc2100	uktr2020	uktr2050
Number of winter tourism days during which the water equivalent of the snow cover is greater than 50 mm									
Altitude range: 900 m-1200 m									
Broye	83.8	64.3	23.2	5.1	75.6	61.5	22.9	66.2	29.8
Ergolz	17.1	9.1	4.8	1.4	10.3	9.0	5.4	9.4	4.9
Murg	36.3	14.8	6.2	1.6	22.9	14.6	6.2	19.9	5.0
Altitude range: 1200 m-1500 m									
Broye	114.7	103.1	91.8	33.7	112.8	102.2	92.1	106.0	83.0
Number of winter tourism days during which the water equivalent of the snow cover is greater than 100 mm									
Altitude range: 900 m-1200 m									
Broye	59.5	38.3	5.3	0.0	48.6	35.1	7.2	48.0	10.8
altitude range: 1200 m-1500 m									
Broye	109.1	84.3	65.7	12.3	94.5	87.1	67.6	96.3	65.5

ertheless, due to the relatively long winter season in these regions the number of days for skiing does not drop below the minimum requirement for the 2050 scenarios at altitudes above approx. 1800 m (see figure 11.1.2.9).

In order to prevent a lack of snow, artificial techniques exist to generate snow on skiing runs. These methods require temperatures below –4°C in order to work efficiently (Witmer, 1986). In regions where resorts already exist it would thus be possible to sustain the snow cover in order to reach the required threshold when temperatures allow this. As these techniques can be used a few days before the tourism period, an inventory of the days during which the snow equivalent is smaller than 100 mm and the temperature lower than–4°C has been carried out for the period from 1st November to 15th April.

Table 14.6.3 shows that some 20 days per extended winter season will fulfil these conditions under the present climate. It also shows that a similar number of days are identified for the 2020 scenarios. Although this number of days is not large enough to sustain the alpine skiing activities in the 900-1200 m range, it seems convenient for the 1200-1500 m range at least in the 2020 climate scenarios. Further into the future (year 2050 and 2100) they seem to be insufficient to balance the GC impact.

This study only responds to very simple thresholds application and thus needs to be taken applied with some caution. A real simulation of the artificial supply of snow and its melting is needed before drawing any final conclusions about a generalised use of artificial snow systems around the alpine skiing runs. Some physical characteristics of the snow on specific land units must be taken into account in order to clearly simulate its evolution, i.e. its slope, orientation, which may require additional developments.

14.7 Case study: impact on the IJsselmeer lake

The IJsselmeer is a freshwater basin at the mouth of the IJssel river, a distributary of the Rhine. It is separated from the Wadden Sea (North Sea) by a barrier (Afsluitdijk). The lake is important for the water management of the surrounding polder areas, for drinking water and

Table 14.6.3 Mean number of days during which the water equivalent of the snow cover is smaller than 100 mm and the temperature lower than –4°C

Scenarios	Present	ukhi2020	ukhi2050	ukhi2100	xccc2020	xccc2050	xccc2100	uktr2020	uktr2050
Altitude range: 900-1200 m									
Broye	23.9	22.3	17.3	6.7	21.8	21.8	16.4	14.8	14.9
Altitude range: 1200 m-1500 m									
Broye	19.5	24.0	21.1	15.3	21.0	19.3	18.7	16.3	15.8

for recreation, while also fulfilling an important function for recreation and ecology purposes. During periods of excess precipitation, water from the surrounding polders is released to the IJsselmeer. The lake's functions depend on the water level in the lake, which in turn is controlled by the water balance of the lake. The water balance is mainly governed by the release of water via the Afsluitdijk barrier towards the Wadden sea, and by the inflow of river (IJssel and Vecht) water. Other, less important components of the water balance are: water upwelling and discharged from the surrounding land, precipitation and evaporation. There are no pumping stations to release water from the lake. Free discharge of water from the lake occurs during periods of low tide, and thus depends on the sea level. Under present day conditions, the target lake level is maintained at 40 cm below sea level during the winter period. This low level is used to achieve sufficient water storage capacity for excess water from the surrounding polders, even during periods of high river discharge. During the summer half year, the water level is kept at 20 cm below sea level to achieve a larger fresh water basin.

All water balance components are affected when the climate changes. In a case study using a water balance model (BEKKEN-2), the effects of climate changes were evaluated for a central estimate in 2050 and for a high estimate in 2100 using the UKHI scenarios. The accompanying sea level changes were obtained from IPCC (1996). The scenarios are summarised in table 14.7.1. Because of the lack of data and scenarios, the effects of changes in wind regime on the water levels could not be taken into account.

Initial model runs for changed climates indicate that:

- The lake level is most sensitive to sea level changes.
- The present low target level of the lake during the winter period cannot be maintained without additional measures.
- Maximum lake levels rise almost linearly with the sea level. According to the central estimate, maximum water levels may increase in the order of 20 cm by 2050.
- During *average* summers, the lake level will only increase slightly over the forthcoming decades.

Table 14.7.1 Climate change and sea level scenarios used for the IJsselmeer. In all cases a target water level during the winter period equal to 0.4 m below Dutch ordnance datum (NAP), and 0.2 m below NAP in summer was used

Scenario		Increase average lake level (m)		Average increase maximum lake level (m)	
GCM run	sea level rise (m)	summer	winter	summer	winter
UKHI-2050 (central estimate)	0.20	0.02	0.10	0.13	0.19
UKHI-2100 (maximum estimate)	0.94	0.34	0.72	0.73	0.95

- During *dry* summers, water demand may exceed the inflow of fresh water via the IJssel. In such situation, the lake level may drop below the target level.

These changes have consequences for the lake's functions:

1. Safety
   An increase of extreme lake levels, and of the design level, will to begin with reduce the safety of the surrounding polders. Secondly, a higher lake level will reduce the possibilities of releasing excess water from the surrounding polder areas into the lake. This may indirectly lead to safety problems within the polder areas as well.
2. Water availability
   Under changed climate conditions, the precipitation deficit in the polder areas will increase during the summer period. Therefore, larger freshwater demand from the IJsselmeer is foreseen during the growing season. However, the input of freshwater via the IJssel river is reduced during the summer period. Consequently, summer periods with high water demand by the surrounding agricultural areas, probably resulting in a water shortage in the IJsselmeer, will occur more frequently and may last longer.
3. Nature and recreation
   A temperature rise will intensify biological processes in the aquatic ecosystems. Biological decay and algae bloom will increase. In turn, this may strongly reduce oxygen concentrations in the water, particularly during warm summer periods. This is unfavourable for both ecology and for recreation.

14.8 Case study: water supply and salinity in the Rhine-Meuse estuary

The lower Rhine-Meuse estuary (Biesbosch-Haringvliet-Rotterdam harbour) has been partly closed from the North Sea by the Haringvliet storm-surge barrier since 1970. The former estuary is presently under minor tidal influence via the New Waterway in the Rotterdam harbour area. The sluices in the Haringvliet barrier are used to control the water flow and salinity within this area. During periods of low river discharge, the sluices are closed, to prevent intrusion of salt water via the open waterway of the Rotterdam harbour. This basin forms an important water supply to prevent salt intrusion in the surrounding polders, and for drinking water. For these purposes, the salinity of the water may not be too high; Chloride concentrations of the water may not exceed 215 g/l. A rise in the sea level, in combination with low flows during the summer period may lead to a progressive intrusion of sea water into the estuary, and hence cause an increase of salinity. The combined effect of sea level rise (S.L.R.) and changed discharge regime of the Rhine river was evaluated using a one-dimensional hydraulic model (ZWENDL). The study was carried out for two freshwater intake stations, one located within the northern part of the area close to the open seaway of Rotterdam, one within the southern part, behind the Haringvliet barrier. Sensitivity tests were carried out for the following scenarios:

- UKHI2020 discharge scenario, with 20 cm S.L.R
- UKHI2050 with 60 cm S.L.R.
- UKHI2100 with 85 cm S.L.R.

Using the model, the number of hours per day that the salinity exceeded the critical level was calculated for varying low discharge stages. For flushing the polders and for agricultural use, salinity should be below the critical value at least about 4 hours per day.

The first model results show quite different effects for the two stations.

- The effect on the southern station (behind the Haringvliet barrier) was only marginal, even under the most extreme scenario. This illustrates the importance of the barrier for the hydrology in this basin.
- The effect on the station close to the open waterway, however, is much greater. Under present day conditions, water intake is limited, on average, only 5 days per year, when the Rhine discharge is lower than 800 m3/s. When sea levels rise by 60 to 85 cm, the minimum discharge required to allow intake of water increases to 1000 m^3/s. Under the UKHI2050 scenario, water intake would not be possible during the summer period for about a month per year, while this figure becomes even worse under the UKHI2100 scenario.

The present method of management of the barrier sluices is unfavourable for the ecology of the former estuary. Therefore, alternative management scenarios are under consideration, comprising various strategies of partly re-opening the sluices in the barrier. The objective of this management method is to increase the tidal dynamics in the basin and to achieve a more natural gradient of salinity. The effects of different scenarios for partly re-opening the dam on salinity, morphological changes, and changes in water levels within the basin, are presently being evaluated. Initial results indicate that the effects of sluice management scenarios are greater than the effects of climate change alone. However, sea level rise and changes in river discharge will interfere with the effects of alternative sluice management scenarios, and they are likely to cause a significant increase of the effects in the southern area. Therefore, the impacts of climate change in combination with alternative water management of the Haringvliet Barrier should be further investigated.

15 Impacts of Climate Changes and Policy implications

This chapter is the key chapter of the CHR study because the impacts of chapter 14 are generalised here and the resulting policy implications in view of the project group are discussed at an adequate level of detail for this study. Chapter 15 is therefore also the main contribution to the second objective of the project: **'PROVIDE GUIDANCE ON THE MANAGEMENT OF WATER RESOURCES IN THE EU UNDER CHANGING CLIMATIC CONDITIONS'**

Some of the derived impacts of climate changes on the hydrology of the Rhine river and its subbasins can be quantified at a semi-detailed level of precision, others however cannot be sufficiently quantified at this stage. Main reasons for this situation are the existing uncertainties associated with the present-day climate scenarios derived from still quite coarse General Circulation Models (GCM) and the representativity of the chosen baseline climate to the total available climate records. Another reason is the insufficient access to information with regard to hydropower generation, irrigation, flood damage, navigation, and other impact areas of socioeconomic importance. Related research gaps are outlined in chapter 17.

15.1 Context for interpretation

Some principal statements have to be made in order to recognise the impact results in their proper context:

15.1.1 With regard to the climate scenarios

It is generally agreed that our climate will change in the forthcoming century, leading to changes in temperature, precipitation and other climate variables in the Rhine basin. However, considerable uncertainties exist with regard to the rate and magnitude of the changes. These are firstly due to uncertainties about future economic developments and greenhouse gas emissions. Secondly, the present-day General Circulation Models (GCM), which form the basis of climate scenarios, are still not able to provide reliable climate scenarios on the regional scale (such as the Rhine basin), nor can they predict statistics of extreme events over small areas. This has resulted in a wide bandwidth of expected changes, especially on a regional scale; without indication of probabilities of occurrence. Changes in temperature, a very important variable in determining the annual discharge regime of the river Rhine, are more reliable than changes in precipitation, which largely determines discharge extremes.

- The scenario simulation results which form the basis of our study may not be regarded as a prediction of the future climate, but must be considered as *what-if scenarios* for a sensitivity analysis on water availability and river regime. For this purpose, various climate change scenarios and different time horizons were considered in this study.

- All simulations assume that the statistical properties of extremes and spatial distributions of precipitation and temperature remain constant under conditions of climate change. As we do not have hard evidence of changes in statistical properties, this assumption is to be seen as a baseline hypothesis which may change in the future when appropriate analytical tools and data become available.

- The impact studies are based on transformations of a baseline climate record, which represents a short time slice of the entire present-day climate record. The results are therefore sensitive to the validity of the baseline scenario, i.e. whether the chosen time period represents both present-day average climate conditions well, and whether it includes extremes that are inherent to the present-day climate.

15.1.2 With regard to the models

- Though estimates of the magnitude of hydrological changes in the Rhine basin vary from model to model, all model results agree on the direction of change. This is a very significant statement as it underlines the scientific validity of the modelling approach: models at different scales and with different concepts were used for the entire Rhine basin and for subbasins, under the assumption that each model used is best suited to reproduce the hydrologic response characteristics of the area that it represents.

- The simulation results are within the range of the applicability of the models used which lends credibility to the applicability of the concepts and algorithms of the hydrological models used in the context of the project.

- To analyse hydrological responses in small basins and especially in alpine regions, and to investigate peak flows, detailed process-oriented models are required. However, given the present reliability of climate scenarios with still considerable uncertainties, simple hydrological models are adequate tools with which to indicate the most vulnerable river functions (including safety, inland navigation, water supply, agriculture, ecology) when considering the basin as a whole.

15.2 Impacts

From the simulations, various impacts on hydrology can be identified. The target period is the year 2050. Several of the identified impacts apply to the Rhine basin as a whole.

15.2.1 Impacts identified for the entire Rhine basin

- Changes in the hydrological regime of the Rhine are so great, that long-term water management strategies should consider the effects of climate changes even when the scenario uncertainties are acknowledged. Climate change is not a phantom invented by scientists!

- Changes in the river regime as a result of climate changes may become apparent in the coming decades.

- The modification of the snow cover (duration, regional distribution, water equivalent of snow) in the Alpine part of the basin is an important effect of climate changes on the discharge regime of the Rhine.

- The hydrological regime of the Rhine will shift from a combined snowmelt - rainfall fed river to a rain-fed river regime.

- Discharge will increase in the winter half year as a result of a significant decrease of precipitation storage in the winter snow cover, and will decrease in the summer half year.

- Peak floods are likely to occur more frequently and become higher, increasing the flooding risk of the hinterland.

- Low flow periods during summer are expected to occur more frequently and last longer. Prolonged low flows will cause problems with quantity and probably also with water quality.

- Increased evaporation and decreased precipitation in summer may lead to a greater soil moisture deficit during summer, which in turn may increase the demand for irrigation water. The reaction of crops to the increased atmospheric CO_2 concentration, and the effect on evapotranspiration is a major uncertainty.

The results of the simulations in drainage basins ranging from alpine to lowland conditions allow an assessment of specific impacts in different parts of the Rhine basin.

15.2.2 Impacts identified for alpine and pre-alpine situations in the upper part of the Rhine basin

- The snow line in the Alps will shift upwards by about 200-400 meters. Winter tourism below 1500 meters will be severely reduced causing serious loss of income for the tourist industry. Additional costly snow machines will have to be installed which may cause damage to the ecology of mountain regions.

- The shift of the snow line is likely to cause the mobilisation of former permafrost soils which then increase the probability of devastating mass movements.

- Winter peak flows in the alpine region will increase sharply because the retention of precipitation in the snow cover is reduced, and the rising snow line allows greater portions of runoff to occur.

- The annual flow volume will remain constant. Increased winter flows will compensate for decreased spring and summer flows for pre-alpine catchments. In the alpine region (as observed at the upstream gauging station of Rheinfelden), differences between mean summer and winter discharges will be smaller. This will facilitate water resources management e.g. with respect to increased flexibility for hydropower generation.

- The probability of floods will decrease in the late spring and summer seasons, under the assumption that the rainfall intensity will not change significantly.

- River basins with a substantial influence from glaciers will be subject to additional glacier melt water discharge. However, decreasing glacier areas will gradually (over the coming decades) contribute less melt water flow to alpine rivers. Consequently, the flow of alpine rivers will not be maintained from glacial meltwater contributions after the ablation of the snow cover in late spring.

- There is a clear signal indicating the increase of the water temperature. Current legal agreements and regulations might be offset by this development if anthropogenic thermal pollution continues at the present level. There is the need to mitigate the effects of water temperature increase to maintain the present agreements for maximum allowable water temperature. The bacteriological situation in rivers and thus the water quality is expected to deteriorate.

15.2.3 Impacts identified for the central part of the basin

- The increased winter discharge due to the decreasing snow storage in the Alpine region will be amplified by increased (liquid) precipitation. This is valid only for the main stem of the Rhine river. In subbasins of the Rhine in this region, major changes in the hydrological regime cannot be detected. One reason for this is the soil moisture deficit at the end of forecast drier summers which dampen the effect of increased winter precipitation.

- In subbasins in the central region, the expected increase of winter precipitation and rainfall intensity will increase the risk of devastating local floods when the precipitation falls on saturated or frozen soils. This is of special importance because most small basins have little or no flood retention areas and technical flood protection works are not as elaborate as along the main course of rivers such as the Rhine, Saar, Mosel and others. It should also be noted that the majority of reported cases of flood damage, at least in the upper part of the central part of the Rhine, occurs in smaller basins outside the major river valleys.

- Peak flows will occur more frequently, increasing the flooding risk.

- Low-flow periods in the main stem of the Rhine during the summer half year will become longer due to two additive effects which amplify the low flow situation: Firstly, with a decrease in snow and glacier melt discharge from the alpine areas, present discharge levels cannot be maintained. Over the years this situation will worsen as the glacier discharge decreases due to the ablation and shrinking of glaciated areas in the Alps. Secondly, the severity of low flows will be amplified as a result of decreasing summer precipitation and increasing evaporation.

- Low flows may particularly affect inland navigation and transport capacity on the middle Rhine stretch from Mainz to Koblenz, where constraints are already experienced during low flows under present-day conditions. This is an economically most important impact, as this impact will be felt at a part of the river stretch with a particularly high tonnage transported on the Rhine between Rotterdam and Basel and vice-versa. On this stretch, the navigation depth is presently only 1.90 meters and there are plans to deepen it by 20 cm to 2.10 meters. A more pronounced low flow is expected to offset the planned deepening of the river.
- Increased evapotranspiration will more often reduce the availability of water to a critical

state in summer. All regions which presently experience problems with groundwater supply will suffer more acute problems due to decreasing groundwater recharge in dry summer periods. The demand for irrigation water will increase, whilst water availability from the river will be reduced. It should be noted that the severity of decreased water availability depends strongly on the reaction of crops to increased atmospheric CO_2 concentrations. This is very uncertain, though it is believed that it will result in more efficient water use by crops.

- Thermal pollution will be an issue with regard to water quality and associated bacterial growth behaviour.

15.2.4 Impacts identified for the lowland part of the basin

- Winter discharge of the Rhine will increase, and summer discharge will decrease.
- Increased peak flows will affect safety in the lower Rhine delta. Though the present models do not provide accurate estimates, the results of this study indicate that the design discharge of the lower river Rhine may by increased in the order of up to 5% by the year 2050.
- Low summer flows will increase the cost of inland navigation between the Rotterdam harbours and the hinterland. The average number of days per year that ships on the Rotterdam-Basel route cannot be fully loaded increases from approx. 14 to approx. 25-30 days per year in 2050.
- In the lowest part of the Rhine delta, sea level rise becomes an additional factor influencing water management. According to the IPCC central estimate, sea level rise may be about 20 cm by the year 2050. A higher sea level in combination with low summer flow is expected to increase problems of salinisation of shallow aquifers and brackish water reaching far in land in coastal regions of the Netherlands. This will adversely affect water demand for agriculture and public water supply.
- Also small lowland rivers show a clear increase of winter discharge, and resulting peak flows. The design discharge may increase by up to 25% in 2050.

15.3 Policy Directions

The second objective of the project is to provide guidance on the management of water resources in the EU in view of climate changes. This chapter therefore aims to provide insight into how we arrived at the policy direction and derived recommendations outlined below.

In presenting policy directions and recommendations it is necessary to recognise that climate change is but one important factor which influences hydrological regimes and thus resultant response strategies. Autochthonous processes such as land use changes due to economic changes and political priorities may mask or even offset the effects of climate change. The feedback mechanisms between change factors on the hydrological regimes of rivers is not well understood and even less quantifiable at present. Therefore, a net change cannot be established. In the long term however, climate changes are expected to have overriding effects on the present short and medium term socio-economic agenda.

Climate change is a slow but persistent process, the rate and magnitude of the changes are still not known. The large annual variability of the climate and its hydrologic response make it difficult to detect these changes over shorter time periods.

In the long run however, the hydrological impact is expected to be so great that it cannot be neglected in water resources planning and management. From the viewpoint of the expected average lifetime of hydraulic structures (weirs, dams, locks, etc.) of about 50-100 years, it is irrelevant whether the present indications of change are in fact an expression of climate variability with a rather large cycle or a genuine climate change: The impacts and policy implications for the envisaged time frame up to the year 2050 are not affected by this distinction.

The uncertainty of GCM scenario outputs

cited at several points in this study would be a critical factor in policy development if they were the only basis of knowledge for policy formulation. It must be understood that present-day water resources management already has mechanisms to cope with extremes, variability and environmental changes. The constraint here is, that the present management practices are based solely on historical records which are not very suitable in coping with expected non-linear changes due to climate change.

Our results demonstrated that the application of the climate change scenarios on hydrological models for representative sub-basins of the Rhine and also the entire Rhine basin allow

(a) the identification of *hot spots* for hydrological impact,

(b) an assessment of the *vulnerability* of river functions (including safety, inland navigation, water supply, agriculture, ecology) for changed climate conditions, and

(c) the evaluation of consequences of climate changes for water resources management.

From the methods available nowadays we expect that General Circulation Models (GCM) which will be available within the next 5-10 years are spatially and temporally more detailed and precise. These improved GCMs may provide new and more accurate climate scenarios. The bandwidth of simulation results in particular is expected to be narrowed down. We expect that new scenarios will support the general trends indicated in our research. New GCMs will allow better quantification of the results and will reduce the amount of uncertainty among different scenarios, and thus in the impact assessment.

Balancing required actions against economic costs and the existing uncertainties in the climate change scenarios, we recommend a policy of 'No Regret' and 'Flexibility' in a pro-active manner.

Policy of No Regret in this context means: Anticipatory adaptive measures are undertaken as a response to the impacts of climate change in combination with on-going activities. At present many measures are proposed and implemented to improve the flood protection. Where possible, so-called win-win situations are created, by combining flood protection with for example ecological rehabilitation of the Rhine river and its basin. Also, measures are taken to maintain and improve the inland navigation possibilities. It is likely that in the future additional measures are required to cope with the impacts of climate change in relation to flood protection, shipping, nature, etc.. Therefore it is important that the measures taken today are flexible towards the future. In other words, it should be possible to adapt and extend them relatively easily for changed conditions. For investments with a long expected life-time, like large weirs or storm surge barriers, the design should take the present knowledge on the possible magnitude of long-term changes into account. Adaptation in a later stage is expected to be much more expensive. Furthermore, actions should be taken in a pro-active way. For example, in the forthcoming period one should increase the system's flexibility in water management of the Rhine river.

Under a Policy of No Regret, a prioritisation of planned or ongoing activities can be considered. ***In other words, pro-active adaption strategies are outlined to respond to the anticipated effects of climate change on the hydrology of the Rhine river and its subbasins.***

The possible policy alternatives: 'Immediate Response' and 'Wait and Verify' are explicitly not recommended. In the first alternative, the scope and extent of responses to climate changes cannot be quantified with sufficient reliability at present. Under the assumption of worst case scenarios, large financial commitments are necessary at a time when the investments cannot be scientifically and economically substantiated. The second alternative would overlook the fact that all indications point to the reality of climate changes, even if hard proof cannot be given by the present knowledge. However, once the changes become evident, the financial means required for a short-term *reactive* response may overcharge the economic capacity of riparian countries. It should be recognised in this respect, that technical responses to increased flood risks require a planning and implementation period of at least 10 years.

15.4 Policy Recommendations

Based on the policy direction of No Regret, our policy recommendations favour pro-active adaptive measures as a response to a progressive change of climate over the next decades, within the time horizon of the study until the year 2050. Therefore, planning strategies should distinguish between time scales of planning and river functions.

15.4.1 Long-term planning

Planning of long-term projects and budgeting of long-term investments must account for the effects of climate changes. Actions that demand a long preparation period should already be initiated by now. In this respect it should be noted that changes in policy may lead to changes in the established legal basis.

The time needed for changes of legislature should not be underestimated. Typical examples for long-term planning scales are floodplain management, land use changes, infrastructural investment in affected areas including harbour facilities, cooling water intakes and abstraction facilities, weirs, locks, bridges etc. and infrastructure in areas prone to flooding (houses, industries etc.). Floods may increase over the forthcoming decades, which demands an additional discharge capacity of the rivers (e.g. by widening or deepening of the river bed), or the provision of flood retention areas. Though the amount of increase cannot be precisely quantified at present, a long-term provisional floodplain management strategy has to be developed which caters for the needs of the immediately affected areas, which and also considering negative downstream effects of these measures.

Purchase of land, changes in land use policies etc. are suitable measures to support floodplain management. Under the policy of no regret, measures would be initiated or accelerated now for reasons mentioned above. Implementation of a larger or smaller extra safety margin should depend on the life-time and possibility of later modification of constructions/measures: In the planning and design of long-term projects and constructions, extra margins that account for the effects of climate change should now already be implemented, in spite of the large uncertainties. This is because adaptation to changed conditions in a later stage may be far more expensive. In long-term planning, in particular, the second pillar of our policy recommendation: *Flexibility*, comes into effect: Flexibility means the definition of designs that can be adapted later on, and preparation for implementation of changes in design.

15.4.2 Short-term planning

In short-term planning, flexibility means that measures which are undertaken now should be flexible, so that they can be adapted according to new insights and demands. For example, nature areas within the winter bed of the river can be more easily adapted to increase the discharge capacity of the channel than built-up areas.

15.4.3 Policy recommendations with reference to river functions

Safety
Counterbalancing a potential higher flood risk under changed climate conditions demands measures to increase the water retention capacity of the river system, and the discharge capacity of the river channels. The restructuring and denaturalisation of riverbeds and flood plains including bylaws regulating floodplain uses are amongst the most powerful strategies to reduce losses due to the expected higher frequency and increase of extreme discharges (floods). With regard to the trend of increasing extremes of discharges, time consuming actions and procedures to reduce flood damage should be initiated in a more pro-active manner.

Water availability

Improvement of water resources management strategies should also include power generation from hydropower plants, irrigation and groundwater recharge. While in alpine catchments the power generation will be facilitated as a result of more evenly distributed flows, power generation in middle and lowland areas will experience productivity losses during low flow periods. Low flows, associated with decreased groundwater recharge, will limit the availability of irrigation water for cash crops and drinking water supply. This situation is already experienced periodically under today's conditions. Our studies also indicate that cooling water demand for thermal power plants may collide with existing regulations with respect to the maintenance of maximum allowable water temperature in rivers.

Inland navigation

Inland navigation should adopt additional flexibility in response to changes in the flow regimes of large rivers. Measures may include shipping schedules, size and weight of the ships, and, as an ultimate and costly option, (partially/temporarily) changing to other means of transport (rail, road).

Legal framework

The legal framework to respond to flood risks is well established in all states along the Rhine river. Due to conflicts between local and regional (downstream) interests, an integrated regional approach to legislate flood protection has been realised only within the past few years and is advocated inter alia by the Commission for the Protection of the Rhine (IKSR). Under the influence of changing hydrological regimes, the legal basis including by-laws and present design principles should be reviewed and reanalysed with respect to its applicability and validity under climate change conditions.

16 Link of the CHR results to the EU dimension of the project

The project has three tiers of investigation:

- The catchment scale, investigating the impact of climate changes on a variety of selected catchments,
- The regional scale, consisting of the Rhine basin, and
- An integrated tier: the direct comparison of catchment results and the regional scale within the Rhine basin.

In this way, the Rhine study forms a link between the different scale levels: Catchment, Region, Europe. The results of the Rhine study are remarkable also in view of the highly heterogeneous catchments ranging from alpine to lowland conditions. These have been described in other chapters of this report.

The link between the regional and catchment scale research results from the CHR investigations and those on the European scale is achieved as follows:

- Using the same climate change scenarios guarantees the consistency of the entire project approach and makes results comparable.
- Downscaling of given climate change scenarios is achieved by interpolation of GCM outputs from 2.5° to 0.5°. The European scale is set at 0.5° × 0.5°.
- Comparison between the RHINEFLOW water balance and the EU scale is possible via upscaling of the results.
- The projected climate change impacts and impact sectors are standardised and harmonised.
- A common set of indicators is used to characterise changes in the hydrological regime of river basins on all scale levels.

17 Priorities of future research - Which way to choose?

Though the study provides a valuable contribution to the project objective, a number of research gaps have become evident. These research gaps need to be filled in order to increase reliability and achieve a more effective quantification of the impact conclusions. A number of the most pressing research gaps, at least in view of the CHR, are identified below.

(1) The present-day climate models are not adequate to provide reliable and accurate scenarios for hydrological impacts. Particularly, the spatial scale of the scenarios should be improved, and precipitation (in particular high-intensity precipitation and summer storms) should be better modelled. Besides, atmospheric and hydrological models should be coupled.

(2) The long-term effect of increased atmospheric CO_2 concentrations on plant physiology, transpiration efficiency, length of the growing season and the use of different crop varieties and resulting net changes in transpiration and inherent soil moisture conditions is not sufficiently known yet. These factors strongly control changes in summer transpiration and the resulting soil moisture deficit during the summer half year.

(3) Hydrological modelling in large river basins still encounters scale problems. Bridging the gap between the coarse-scale conceptual water balance models on full-basin scale and high-resolution physically based models that are currently only available for small subcatchments is still a major task for the forthcoming years. Model requirements for water management, data requirements and availability for model calibration and validation, sophistication of model concepts, and computing capacity, all these must be brought in balance; the latter with a somewhat lower priority.

(4) Re-scaling of monthly data to daily conditions and especially in the alpine region hourly temporal resolution scales have to be achieved in a more realistic way.

(5) Besides the scale issue, the direction and extent of changes in the statistical properties of time series e.g. for precipitation under climate change conditions must be investigated in much more detail. This assessment is necessary to quantify hydrological extremes and their probability of occurrence with a higher degree of reliability.

(6) Considerable research efforts are necessary to overcome a particular shortfall of climate impact modelling where climate changes are considered without concurrent other changes in the basin: Climate change scenarios should also be considered in combination with other autonomous socio-economic developments such as land use changes, urbanisation and water control structures and measures for navigation. Such autonomous developments may mask, override or amplify effects resulting from anthropogenic climate changes. The feedback mechanisms between these factors are poorly understood and quantified at present.

As far as the CHR is concerned, a number of results are expected from ongoing and planned further studies:

(a) Probability of hydrological extreme events under present and changed conditions is quantified.
(b) Vulnerability of selected river functions (e.g. inland navigation, freshwater supply, power generation, water level control in polders) is evaluated with present operation rules as a reference.
(c) Incurred costs due to the occurrence of extreme hydrological events under present and changed conditions for selected river functions are assessed.
(d) Further and perhaps modified strategies for the adaptation of water regulation, flood/drought mitigation (flood retention) to sustain the river functions are developed on the basis of existing plans and requirements under climate change conditions.
(e) Re-assessment of existing management strategies under the changed conditions is carried out.

As a direct result of the present study, the following activities are planned in order to achieve some of the results outlined above:

- Include more glaciated alpine river basins.
- Determine the sensitivity of peak floods to changes in precipitation intensity.
- Develop a quantitative measure of uncertainty to model results.
- Improve the present RHINEFLOW model to a hydrological model on a 10-day basis.
- Improve parametrisation techniques of hydrological models (catchment and grid scale).
- Evaluate statistical downscaling techniques in order to estimate peak-flow probabilities; evaluate 'cost-benefit' for detailed models.
- Provide more specific and detailed analysis of extreme events (floods and droughts) including modification of rain intensities.
- Investigate trends in water temperature and model climate scenario - water temperatures.
- Give detailed analysis about the most sensitive category of inland navigation.
- Estimate impact of regime changes on hydropower generation for hydropower plants in the Rhine basin.
- Provide sensitivity analysis on spatial and temporal scales in order to assess impacts of climate/land use change for improved RHINEFLOW model and conceptual lumped models.
- Assess, whether changes of hydrological variables exceed natural variation/variability: This issue must be specified with regard to the length of the time series (available observation periods).

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DIREN	Direction Régionale de l'Environment Lorraine, Metz
EU	European Union, DG XII, Dr. Balabanis
KNMI	Royal Dutch Meteorological Institute, de Bilt
LfU	Landesanstalt für Umweltschutz des Saarlandes (State Department of Environmental Protection), Saarbrücken
LfW	Landesamt für Wasserwirtschaft (State Department of Water Resources), Mainz
LHG	Swiss Hydrological and Geological Survey
L + T	Swiss Federal Office for Topography
PROV	Province of Overijssel
SMI	Swiss Meteorological Institute
SNS	Service de la Navigation, Strasbourg
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I-2 GERHARD, H.; MADE, J.W. VAN DER; REIFF, J.; VREES, L.P.M. DE (1983): Die Trocken- und Niedrigwasserperiode 1976. (2. Auflage 1985) / La sécheresse et les basses eaux de 1976 (2ème édition, 1985). ISBN 90-70980-01-0

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Enige gegevens betreffende de:

INTERNATIONALE COMMISSIE VOOR DE HYDROLOGIE VAN HET RIJNGEBIED (CHR)

Oprichting

1970 In het kader van het Internationaal Hydrologisch Decennium (IHD) van de UNESCO.

1975 Voortzetting van de werkzaamheden in het kader van het Internationaal Hydrologisch Programma (IHP) van de UNESCO en het Operationeel Hydrologisch Programma (OHP) van de WMO.

1978 Ondersteuning van het werk van de Commissie door een nota-uitwisseling tussen de samenwerkende landen.

Taken

- Bevordering van samenwerking tussen hydrologische instituten en diensten in het stroomgebied van de Rijn.
- Uitvoeren van hydrologische studies in het Rijngebied en uitwisseling van de onderzoeksresultaten.
- Bevorderen van de uitwisseling van hydrologische gegevens en informatie in het Rijngebied (bijv. actuele gegevens, voorspellingen).
- Ontwikkeling van standaardmethoden voor het verzamelen en bewerken van hydrologische gegevens in de Rijnoeverstaten.

Deelnemende landen

Zwitserland, Oostenrijk, Bondsrepubliek Duitsland, Frankrijk, Luxemburg, Nederland

Voertalen

Duits en Frans

Organisatie

Vaste vertegenwoordigers (vergaderingen tweemaal per jaar) ondersteund door een permanent secretariaat. Onderzoeken worden door rapporteurs en internationale werkgroepen uitgevoerd.

Some information on the:

INTERNATIONAL COMMISSION FOR THE HYDROLOGY OF THE RHINE BASIN (CHR)

Foundation

1970 Within de framework of UNESCO's International Hydrological Decade (IHD).

1975 Continuation of activities in the framework of UNESCO's International Hydrological Programme (IHP) and the Operational Hydrology Programme (OHP) of WMO.

1978 Support of the Commission's activities by exchange of a verbal note between the participating countries.

Tasks

- Support of co-operation between hydrological institutes and services active in the catchment area of the Rhine.
- Executing hydrological studies in the Rhine basin and exchange of research results.
- Promoting the exchange of hydrological data and information in the Rhine basin (e.g. current data, forecasts).
- Development of standardized methods for collecting and processing hydrological data in the Rhine riparian states.

Participating countries

Switzerland, Austria, Federal Republic of Germany, France, Luxemburg, the Netherlands

Working languages

German and French

Organization

Permanent representatives (meetings twice a year) supported by a permanent secretariat. Studies are carried out by rapporteurs and international working groups.

Belangrijkste lopende onderzoeken

'*Klimaatveranderingen*'

- Ontwikkeling van een waterhuishoudkundig model voor de Rijn.
- Analyse van de invloed van klimaat- en landgebruikgsveranderingen op gemiddelde en extreme afvoeren.
- Vastellen van beperkende maatregelen.

'*Sediment*'

- Verbetering en standaardisering van meetmethoden voor gehalten aan zwevend materiaal en bodemtransport.
- Beschrijving van de sedimenthuishouding in de rivier.
- Kennisuitwisseling op het gebied van morfologische modellering.

'*GIS*'

- Vervaardiging van een digitale Monografie van de Rijn door samenvoegen van beschikbare nationale thematische gegevens.

'*Veranderingen in het afvoerregime*'

- Beschrijving van de invloed van menselijke activiteiten op de Rijnafvoeren
- Bepaling van de invloed van veranderingen in bodemgebruik en klimaat op het afvoerregime van de Rijn.

'*Stroomtijden*'

- Bepaling van de stroomtijden en stoftransport in de Rijn ter verbetering van het alarmmodel voor de Rijn (in samenwerking met de IRC).

'*Extreme gebeurtenissen*'

- Beschrijving van oorzaken, verloop en gevolgen van extreme hydrologische gebeurtenissen.

Afgesloten onderwerpen

zie lijst van publikaties, blz. 168

Selection of current subjects

'*Climate changes*'

- Development of a water management model for the Rhine.
- Analysis of the impact of climat and land use changes on average and extreme discharges
- Identification of mitigating measures.

'*Sediment*'

- Improvement and standardization of methods to measure suspended load and bed-load transport.
- Description of sediment characteristics of the river.
- Echange of knowledge on morphological modelling.

'*SIG*'

- Realisation of a digital Monograph of the Rhine by joining available national thematical data sets.

'*Changes in the discharge regime*'

- Description of the impact of human activities on the Rhine discharges.
- Determination of the effect of changes in land use and climate on the discharge regime of the Rhine.

'*Travel times*'

- Determination of the travel times and constituent transport in the Rhine for the improvement of the alarm model for the Rhine (in co-operation with CIPR/IKSR).

'*Extreme events*'

- Description of causes, course and consequenses of extreme hydrological events.

Completed projects

see list of publications, p. 168

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