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

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Abstract. The International Commission for the Hydrology of the Rhine basin (CHR) has carried out a research project to assess the impact of climate change on the river flow conditions in the Rhine basin. Along a bottom-up line, different detailed hydrological models with hourly and daily time steps have been developed for representative sub-catchments of the Rhine basin. Along a top-down line, a water balance model for the entire Rhine basin has been developed, which calculates monthly discharges and which was tested on the scale of the major tributaries of the Rhine. Using this set of models, the effects of climate change on the discharge regime in different parts of the Rhine basin were calculated using the results of UKHI and XCCC GCM-experiments. All models indicate the same trends in the changes: higher winter discharge as a result of intensified snow-melt and increased winter precipitation, and lower summer discharge due to the reduced winter snow storage and an increase of evapotranspiration. When the results are considered in more detail, however, several differences show up. These can firstly be attributed to different physical characteristics of the studied areas, but different spatial and temporal scales used in the modelling and different representations of several hydrological processes (e.g., evapotranspiration, snow melt) are responsible for the differences found as well. Climate change can affect various socio-economic sectors. Higher temperatures may threaten winter tourism in the lower winter sport areas. The hydrological changes will increase flood risk during winter, whilst low flows during summer will adversely affect inland navigation, and reduce water availability for agriculture and industry. Balancing the required actions against economic cost and the existing uncertainties in the climate change scenarios, a policy of 'no-regret and flexibility' in water management planning and design is recommended, where anticipatory adaptive measures in response to climate change impacts are undertaken in combination with ongoing activities.

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1. Introduction

Water management planners are facing considerable uncertainties on future demand and availability of water. Climate change and its potential hydrological effects are increasingly contributing to this uncertainty. The Second Assessment of the Intergovernmental Panel on Climate Change (IPCC, 1996) states that an increasing concentration of greenhouse gases in the atmosphere is likely to cause an increase in global average temperature of between 1 and 3.5 degrees Celsius over the forthcoming century. This will lead to a more vigorous hydrological cycle, with changes in precipitation and evapotranspiration rates regionally variable. These changes will in turn affect water availability and runoff and thus may affect the discharge regime of rivers. The potential effects on discharge extremes that determine the design of water management regulations and structures are of particular concern, since changes in extremes may be larger than changes in average figures.

Climate change may potentially have major consequences for the use and water management of the River Rhine (Kwadijk, 1993). The Rhine basin measures 185,000 km^2 and includes densely populated and highly industrialised areas. The river is of great economic and environmental importance for the riparian countries. It is the busiest waterway for inland navigation in Europe, and its water is used for a wide range of sectors, such as hydropower generation, agriculture, industry and domestic water use. The Rhine river system also constitutes a major transnational ecological corridor. The major floods in 1993 and 1995 that caused huge damages along the entire river and dry summers in recent years have revealed the vulnerability of water management systems to changes in hydrological regime of the Rhine. Regarding the potentially large socio-economic impacts, it has become recognised that climate induced changes in the discharge regime of the Rhine should become factored into water management (IKSR, 1995) and so the need for impact assessment has arisen.

2. Modelling Approaches in Climate Impact Studies

Over the past decennium many studies into the impacts of climate change on water resources have been carried out (Leavesley, 1994; Arnell, 1998). These studies all have used models to translate the assumed climate changes into hydrological responses. Depending on the objectives of the study, the spatial and temporal scales, and the data availability, different model conceptualisations and parameterisations have been applied (Leavesley, 1994). Gleick (1987a,b) developed a monthly water balance model for application in the Sacramento basin. His study indicated that in spite of annual precipitation increases, temperature rise could cause a shift from summer to winter discharge. Arnell (1992) used a similar type of model in catchments within the U.K. to estimate changes in monthly river flow and to analyse the factors controlling the effects of these changes. Arnell (1998) indicated that discharge may decrease in southern Britain, while in northern Britain it may increase, particularly during winter. Kwadijk (1993) developed a monthly water balance model to compare the hydrological impacts in the Rhine basin for different climate scenarios (Kwadijk and Rotmans, 1995). The results indicated that the Rhine regime might shift from mixed snowmelt-rainfall to a rainfall dominated regime. Bultot et al. (1988) developed a lumped-parameter model (IRMB) with a daily time step that considers the transfer from precipitation to runoff, including processes such as interception, evapotranspiration, and the partitioning of water into different runoff components in a more conceptual way. This model was applied to basins in Belgium (Bultot et al., 1988; Gellens and Roulin, 1998) and Switzerland (Bultot et al., 1994). The results demonstrated the importance of the geo-hydrological conditions of catchments on the effects of the applied climate changes. An increase in peak flow frequency was observed in most cases. A similar modelling concept was used by Mimikou et al. (1991) and Panagoulia (1992) in Greek catchments, where mountainous catchments showed reductions in annual and, more severely, summer runoff. The HBV model (Bergström, 1976), presently using spatially distributed data (Lindström et al., 1997), has been applied in many Scandinavian catchments (Bergström and Lindström, 1998). Modelling projects to study large-scale climate-induced changes in hydrological budgets, such as in the framework of GEWEX (Global Energy and Water Cycle Experiment) (Lawford, 1998) and the BALTEX project (e.g., Bergström, 1998) have been initiated in recent years.

Climate impacts not only depend on the changes in water resources, but also on the present-day pressure on water, and the degree of adaptation that can be accommodated within the water management system (Arnell, 1996, 1998). Examples of regional climate impact studies that addressed issues on the water demand side are the McKenzie Basin Impact study (Cohen, 1995), a study on water resources in Britain by Arnell (1998), and climate impact analysis on the Great Lakes in the U.S.A. and Canada (Mortsch, 1998).

3. The Rhine Basin Study

In 1989 the International Commission for the Hydrology of the Rhine basin (CHR) initiated a research project for the development of a water management model for the entire Rhine basin (Parmet et al., 1995). Several institutes of the Rhine riparian states co-operate in the project. The model should enable assessing the impact of climate change on the river Rhine. To estimate changes in peak flows, a temporal resolution of the model of one day was desired. Regarding the difficulties envisaged when developing a detailed model for a basin as large as the Rhine basin, the following approach was chosen. Along a bottom-up line several detailed models were developed for several sub-catchments, while along a top-down line a coarse water balance model was developed for the entire Rhine basin. Using this set of models, the effects of climate change on the discharge regime in various parts of the Rhine basin were calculated for different climate scenarios. This paper presents the impact of selected climate scenarios on the hydrological regime of the river Rhine and discusses similarities and differences between the model results. The results of this study have been extensively reported in Grabs et al. (1997).

4. Method

The Rhine basin covers an area of 185,000 km^2 (Figure 1) and can be subdivided into three major hydrological areas: the Alpine area, the German Middle Mountain area and the Lowland area. Detailed hydrological models with a physical basis that use a daily or shorter time step have been developed for representative sub-catchments ($<$5,000 km^2) within each of these three areas. These models are suitable to analyse the effects of changes in climate and land use on average, low and peak discharges in the sub-catchments. A coarse scale water balance model, RHINEFLOW, has been developed for the entire Rhine basin. This model enables investigation of the effects of climate changes on monthly average discharges for the entire river Rhine and its main tributaries.

4.1. STUDY AREAS

The catchments for which the detailed models were developed are shown in Figure 1 and their main characteristics are summarised in Table I. The alpine catchments include the Alpine and pre-Alpine parts of the Rhine basin, with an altitude range between 300 and 2500 m. In these areas, snow storage and snow melt strongly influence the annual cycle of runoff. Precipitation intensities show a high spatial variability, associated with the large differences in elevation. The Middle Mountain catchments are part of the Mosel basin, and cover an altitude range between 150 and 700 m. The Vecht catchment in the lowland part of the Rhine basin has only minor elevation differences. Here, the sub-soil consists of permeable sedimentary deposits, so that groundwater is an important component in the water balance of the catchment.

To enable the development of the RHINEFLOW model and the sub-catchment models a comprehensive database has been established containing the topographical, meteorological, hydrological and land use conditions of the entire Rhine basin on a very detailed scale using a Geographic Information System (GIS). To make results comparable, many efforts were put into making the data consistent among the participating countries, e.g., the re-classification of land use maps.

4.2. DESCRIPTION OF THE MODELS

For the analysis of the detailed catchments, existing rainfall-runoff models were applied, because their concepts and performances had been proven adequate in earlier applications. In view of their application for changed climate conditions,

TABLE I

Characteristics of the investigated sub-catchments in the Rhine basin

Area (km^2)		Altitude range (m a.s.l.)			Land use type coverage (%)				Annual precip. (mm)	Annual evapotr. (mm)	Annual runoff (mm)
		Max	Avg	Min	Forest	Pasture	Meadow + arable	Urban			
Thur	1700	2504	769	356	29	9	52	8	1450	560	890
Murg	212	1035	580	390	29	0	62	8	1220	600	620
Ergolz	261	1169	590	305	40	4	51	5	1080	640	440
Broye	392	1514	710	441	25	2	67	5	1300	710	590
Prüm	150	700	435	150	33	0	55	5	900	460	440
Blies	205	545	330	205	53	0	41	6	930	590	340
Vecht	3800	110	30	5	20	0	75	5	780	495	285

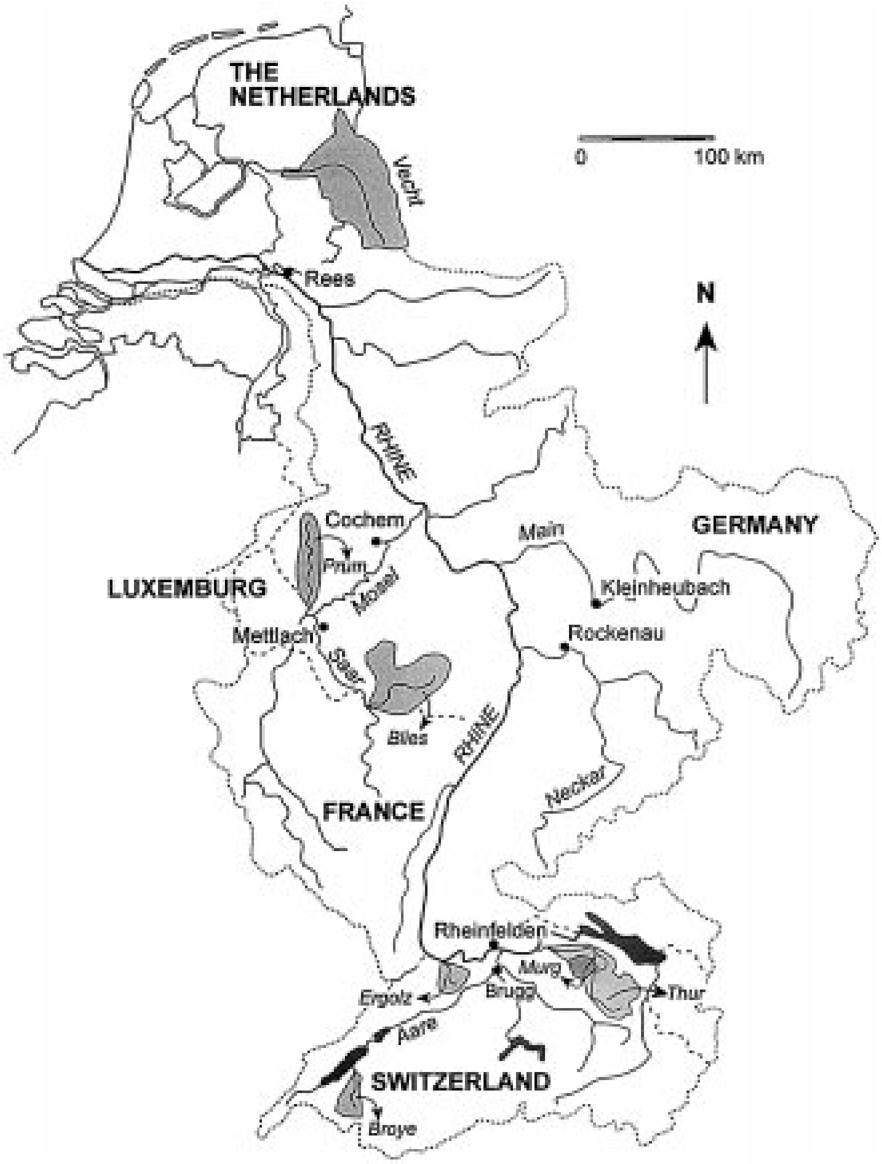

Figure 1. Location of the investigated catchments and gauging stations in the Rhine basin.

all these models were conceptual or physically based, with a varying degree of detail, and they have been adapted to the specific physical conditions of the catchments. The detailed models comprise about 10 to 15 parameters each. These have been calibrated separately for different hydrological components, such as snow melt (Alpine models) or ground water storage (Lowland model). A more extensive

TABLE II

Summary of the model characteristics

	Thur	IRMB	Saar	Vecht	RHINEFLOW
Temporal resolution	1 h	1 day	1 day	1 day	1 month
Spatial resolution	100 × 100 m[a]	100 × 100 m[a] lumped with 8 hydrotopes	30 × 30 m[a]	250 × 250 m	3 × 3 km
No. of land use types	10	8	12	12	5
Number of meteo stations	22	1	15	1	27
Climate data[b]	T,P,e,u,G	T,P,Ts,e,u,G,Hs	T,P,e,u,G	T,P,A,e,S,u	T,P
Reference period	1981–1995	1981–1993	1961–1990	1965–1990	1956–1980
Snow accumulation	Radiation and wind correction, Anderson (1973) and Temp-index	Energy balance	Energy balance	Not included	Linear temperature relationship
Evapotranspiration	Penman–Monteith	Modified Penman–Monteith	Modified Penman–Monteith	MUST (Penman–Monteith)	Thornthwaite
Groundwater infiltration and recharge	TOPMODEL approach	Multiple storages model	Percolation to deep ground water is lost from system	2-D steady state ground water model	Recession term
Runoff	TOPMODEL, separation of overland flow and base flow	Separation of overland flow and base flow	Separation of overland flow and base flow	Wageningen Model: separation of overland flow and base flow	Water balance separation of overland flow and base flow by divider
Flow routing	Translation-diffusion	Unit hydrogrammes	Pulse model	Muskingum	Not included

[a] Resolution of land use, which may be different for soil data.

[b] T = temperature; P = precipitation; e = water vapour pressure; u = wind speed; G = global radiation; A = air pressure; Hs = snow depth.

description of the models is given in Grabs et al. (1997). Table II summarises the models used.

4.2.1. *WaSiM-ETH Model for the Thur Catchment*

For the Thur catchment a distributed model with an hourly time step was used. Specific attention was paid to the interpolation of meteorological data in this mountain region with varying altitude, slope, aspect, and wind speed, and with shadowing effects and inversions. Runoff is calculated using the WaSiM-ETH model. This model is based on the TOPMODEL (Beven and Kirkby, 1979; Beven et al., 1984), with three substantial modifications: (1) calculation is carried out in a distributed way, (2) a fast subsurface flow component and fast interflow are distinguished, and (3) evapotranspiration losses in the root zone can be replenished by water uptake from the saturated zone and from the interflow storage. The model structure, parameter estimation and model performance are extensively described by Schulla (1997) and Gurtz et al. (1997).

4.2.2. *The IRMB Model for Murg, Ergolz, Broye*

The IRMB model (Integrated Runoff Model – F. Bultot) has been devised by the Hydrology Section of the Royal Meteorological Institute of Belgium (Bultot and Dupriez, 1976a,b, 1985) to simulate the components of the water cycle in medium-sized catchments. The input data, in particular rainfall, are considered uniform over the entire catchment (surface areas ranging from 200 km^2 to 1500 km^2). The IRMB model is based on a cascade of sub-reservoirs representing the various main water storages of the catchment (including snow storage) and the transfers between them. It calculates river discharge at a daily time step. The full description of the equations is discussed in Bultot and Dupriez (1976a,b) and Bultot et al. (1994).

4.2.3. *Saar Model*

For the low mountain range of Germany, the Hydrological Simulation Program Fortran (HSPF; PC version, release 10) was used. A detailed description is given in Bicknell et al. (1993). HSPF is a semi-distributed conceptual model, based on hydrological response units. The model included snow accumulation and snow melt processes. Calculation of potential evaporation for each land use is done via an evaporation model developed at BfG (Liebscher et al., 1995). Flood routing is done using the modified pulse method.

4.2.4. *Vecht Model*

The lowland model describes processes that are directly influenced by climate and land use changes, such as evapotranspiration, in a physically based way. Processes indirectly influenced by climate, e.g., transport of water through the drainage system, are described in a more conceptual manner. Snowmelt is not incorporated in the model. Actual evapotranspiration and ground water flow processes are modelled by physically based steady state models, one for the unsaturated zone (De Laat, 1992), and one for the saturated zone (De Lange, 1991). A conceptual rainfall-runoff model ‘Wageningen model’ (Warmerdam et al., 1993) calculates runoff. Flood routing is simulated using the Muskingum method.

4.2.5. *RHINEFLOW Model*

The RHINEFLOW model is a raster-based water balance model with a spatial resolution of 3 km × 3 km that was developed for the entire Rhine basin (Kwadijk, 1993). For each grid cell, the model calculates on monthly basis the storages and transfers from precipitation to runoff, using the major water storage compartments snow, soil, groundwater and lakes. Basin stream flow is obtained by adding the net water production for all cells located in a catchment. Assuming that all water available for runoff leaves the catchment within one time step, the model produces month to month runoff for the River Rhine and for its main tributaries. The model has been implemented in a GIS using generic functions. It has been calibrated for three parameters: (1) separation between runoff and groundwater discharge, (2) flow recession, and (3) snowmelt rates per degree temperature rise. The latter has been calibrated independently using snow cover data. Model structure, data requirement and model performance are discussed in detail by Van Deursen and Kwadijk (1993).

All models have been validated and calibrated in split-sample tests using observed time series of input data and output discharge (cf. Klemes, 1986). Efficiency coefficients and correlations between observed and simulated discharge varied between 0.8 and over 0.9 for the verification periods, which indicated that all models performed well for the area and at the resolution they were designed for. Extensive descriptions of the procedures followed and the validation results can be found in Grabs et al. (1997).

4.3. CLIMATE CHANGE SCENARIOS

Climate change scenarios have been provided by the Climatic Research Unit, University of East Anglia with the assistance of the Institute of Hydrology, Wallingford. The construction of these scenarios is based on two General Circulation Models (GCM), the Hadley centre's high-resolution 11-layer atmospheric GCM (UKHI), and the Canadian CCC model (referred to as XCCC) (Hulme et al., 1994). The procedure suggested by Santer et al. (1990) was followed in establishing the scenarios. Using each model, a control integration for present day greenhouse gas concentrations was made, as well as a run with doubled CO_2-concentrations. From the results, climate change fields that indicate climate changes per degree global warming were generated. These have been rescaled according to the global warming resulting from a doubling of CO_2 concentrations, simulated using a simple energy balance model MAGICC (Wigley and Raper, 1992), assuming the IPCC emission scenario IS92a with a global climate sensitivity of 2.5 °Celsius, while ignoring the effect of sulphate aerosols. For each scenario, anomalies of mean monthly temperature, precipitation, wind speed, radiation, and vapour pressure have been determined for the year 2100. These were interpolated down to a grid resolution of 0.5° × 0.5° longitude/latitude. Climate anomalies for

TABLE III

Changes in temperature and precipitation in different parts of the Rhine basin according to the UKHI and XCCC experiments, projected to the year 2050

		Alpine area			Central Germany			Lowland area		
		Y	W	S	Y	W	S	Y	W	S
UKHI	dT (°C)	2.2	2.3	2.0	2.1	2.4	1.9	2.0	2.3	1.6
	dP (%)	1.8	8.6	–5.1	5.4	12.6	–1.9	11.0	17.7	4.5
XCCC	dT (°C)	1.6	1.6	1.7	1.3	1.2	1.3	1.0	1.0	1.0
	dP (%)	4.9	9.5	–3.0	4.5	11.0	–2.0	4.8	10.1	–0.4

Y = year; W = winter (Nov.–Apr.); S = summer (May–Oct.).

the years 2020 and 2050 have been obtained by linear scaling of the results obtained for 2100.

The monthly climate anomalies have been applied to the available base-line climate series in a straightforward way. Temperature changes were added as absolute changes to the base line series; the other climate parameters were adapted according to their relative changes. Table III shows the changes in P and T, projected to the year 2050 according to the UKHI and XCCC climate scenarios for different parts of the Rhine basin. All scenarios envisage an increase in annual precipitation, due to an increase of winter precipitation. The temperature rise according to the UKHI scenario is in the order of 2 °C, with a greater rise in winter than in summer. The XCCC scenario gives a temperature increase by about 1–1.5 °C. The UKHI scenario is drier than the XCCC scenario in terms of atmospheric vapour saturation. Overall, the XCCC experiment yielded the more moderate changes of the two.

5. Results

5.1. CHANGES AT THE RHINE BASIN SCALE

Figure 2 shows the hydrologic responses obtained using the RHINEFLOW model for the UKHI and XCCC scenarios for different stations along the Rhine and its main tributaries. The hydrograph for the entire basin (station Rees) shows a rise of winter flow and a reduction of summer flow. Within the basin, the largest increases in winter flow are found for the Alpine area (Brugg, Rheinfelden). When going from the Alps downstream along the Rhine, the winter increase is damped because of the smaller increase in winter flow from the tributaries (Neckar, Main, Mosel) in Germany, but still is present in Rees. The reduction in summer flow is largest in the Alps, too. In the central part of the basin, the RHINEFLOW model indicates a small decrease of summer flow, such that this reduction is still present at the Rees station downstream. The UKHI scenarios generally resulted in greater changes

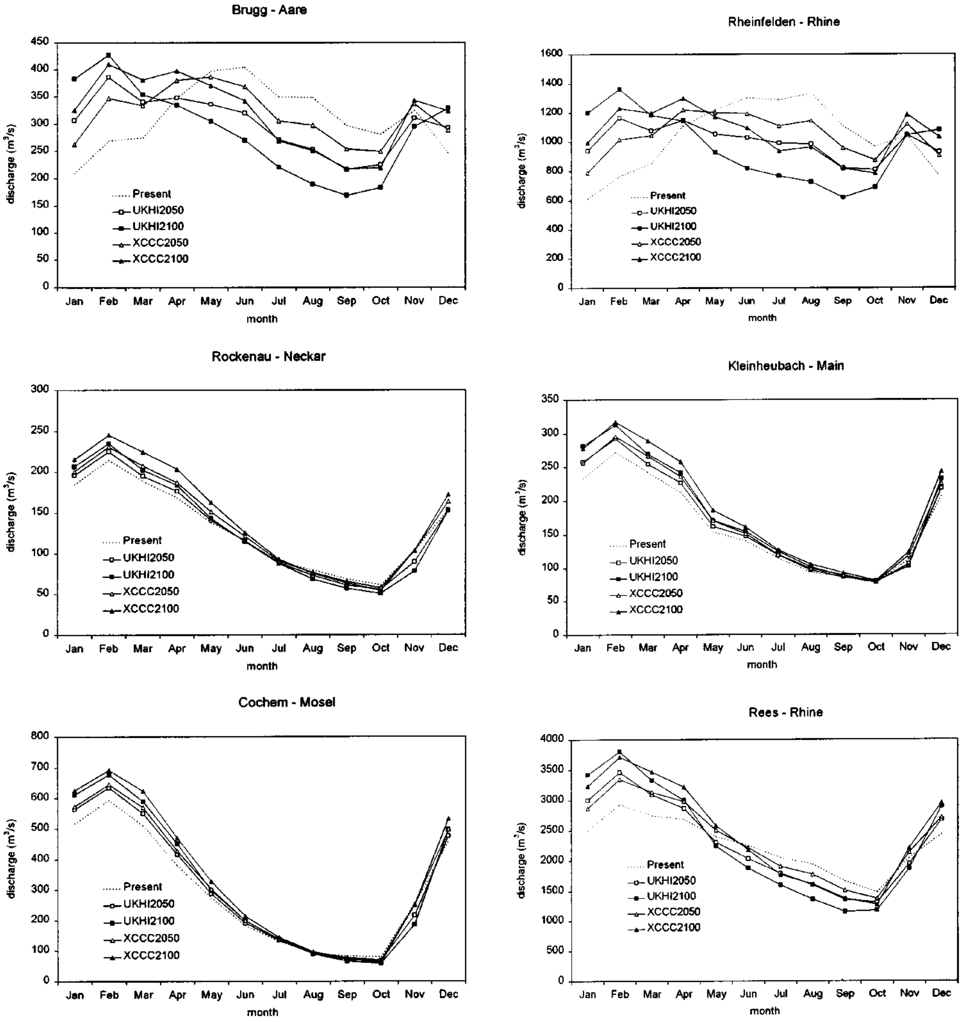

Figure 2. Monthly average discharge at different gauging stations in the Rhine basin for the UKHI and XCCC scenarios, calculated using the RHINEFLOW model. Alpine area: Brugg (Aare) and Rheinfelden (Rhine); main tributaries in Germany: Rockenau (Neckar), Kleinheubach (Main), Cochem (Mosel); entire basin: Rees (Rhine).

than the XCCC scenarios. Nevertheless, both climate models indicate a shift of the hydrological regime in the entire Rhine basin. In the upper Alpine area the intra-annual difference between low winter flow and high summer flow decreases (and even may be inverted), while in the lower parts the existing summer-winter differences are amplified.

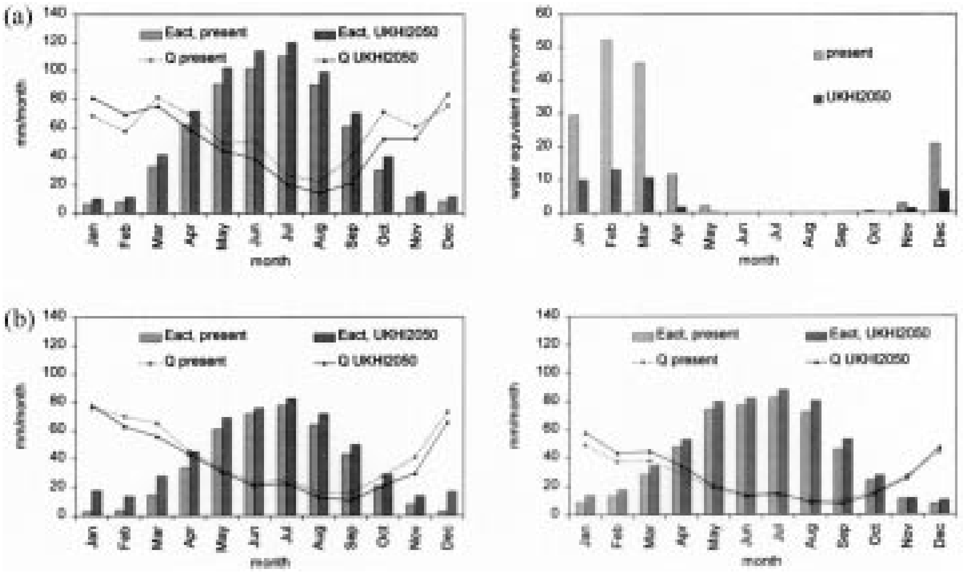

Figure 3. Hydrological changes at the catchment scale in different parts of the Rhine basin according to the UKHI scenario projected to the year 2050, based on the detailed models. (a) = Alpine area – Broye catchment, left: monthly actual evapotranspiration and discharge (mm); right: monthly snow storage (water equivalent, in mm). (b) = Left: German Middle Mountain area – Prüm catchment, monthly actual evapotranspiration and discharge (mm); right: Lowland area – Vecht catchment, monthly actual evapotranspiration and discharge (mm).

5.2. CHANGES AT THE CATCHMENT SCALE

Figure 3 shows the changes in monthly discharge according to the UKHI2050 scenario for different parts of the Rhine basin, based on the detailed models. The main trends that were found per subregion within the Rhine basin can be summarised as follows.

5.2.1. *Alpine Area*

In the Alpine area, higher temperatures will reduce the amount of snow accumulation during winter. This results in higher winter discharge, and lower summer discharge. In addition, winter precipitation increases, while precipitation may decrease in some summer months. Higher temperatures will intensify evapotranspiration, particularly during summer. On an annual basis, this increase is larger than the precipitation increase, resulting in a reduction of annual runoff. When comparing responses of the different catchments in more detail, major differences show up. 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, however, this increase is less significant. Changes in summer peak flows could not be well determined by the models, since these are largely generated by convective storms, which demands a much finer temporal and spatial modelling scale. Summer minima decrease in all cases.

5.2.2. *German Middle Mountains Area*

In the German Middle Mountains, the investigated catchments demonstrate only a minor seasonal shift in river flow. The changes in runoff are controlled by the balance between increased precipitation on the one hand, and increased evapotranspiration rates due to higher temperatures on the other hand. This balance depends both on the expected climate changes and on the present climate and land use. In the investigated cases, the accelerated evapotranspiration seems to counterbalance the higher precipitation, resulting 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 recharged by precipitation. Peak flows resulting from heavy rainfall and convective thunderstorms, however, are expected to increase. The differences in response between catchments are considerably smaller than in the Alps.

5.2.3. *Lowland Area*

In the lowland area, increased winter precipitation will cause higher winter discharge and winter peak flows. Under conditions of the UKHI2050 scenario, annual peak flows increase by the order of 20%. During summer, higher evapotranspiration levels cause a net precipitation deficit, reducing discharge in late summer by about 5%. It may take several weeks before the deficit in groundwater storage is replenished by precipitation.

6. Discussion: Comparison of Modelling Results

In addition to the general trends described above, this study also examined the effects of different modelling resolutions, differences in the level of detail in which the models represented the hydrological processes, different climate scenarios, and the characteristics of the investigated catchments. These are discussed below.

6.1. COMPARISON OF MODEL RESULTS AT DIFFERENT SCALES

It should be emphasised here that the comparison does not aim at identifying model errors, or bad performance of a model. Each of the models has been tested and has proved to be adequate for the catchment and the scale it was developed for. The comparison, therefore, focuses on analysing to what extent and why different model concepts and modelling scales influenced the model results. When considering the changes in river flow on a monthly basis, the general trends found using the high-resolution models are similar to those obtained using the coarse

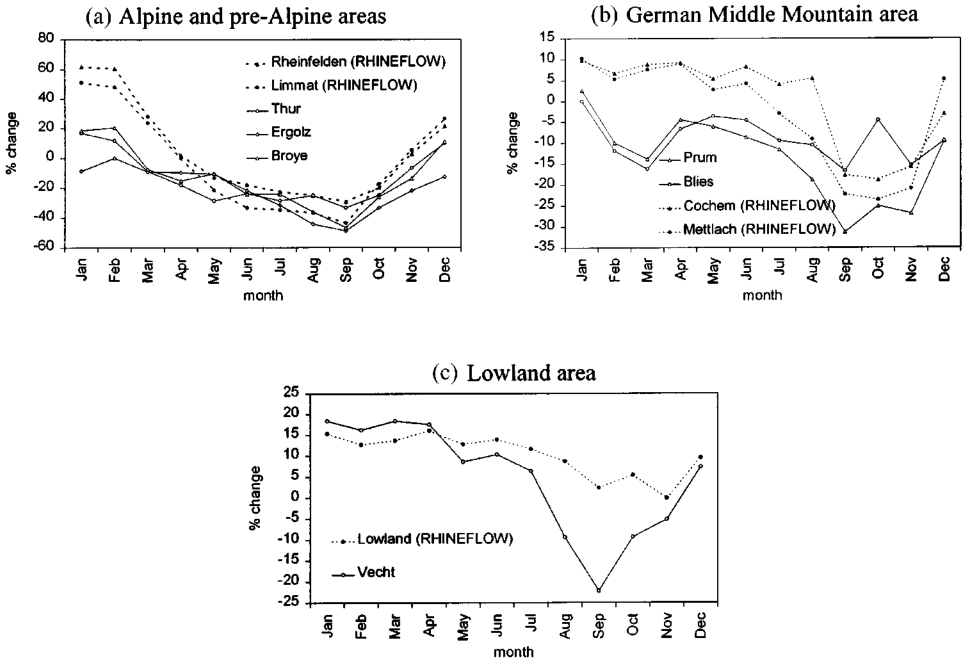

Figure 4. Comparison of the results of the RHINEFLOW model with the detailed models for the UKHI2050 scenario – changes in monthly average discharge (%).

RHINEFLOW model. The degree of the changes, however, is sometimes different. In Figure 4 a comparison is made on the basis of the UKHI2050 scenario.

For the Alpine area, the RHINEFLOW model envisages a larger increase of the winter discharge than the detailed models. This may reflect a larger contribution of changes in the amount of snow storage during winter. The area on which the RHINEFLOW results were based included the highest parts of the Alps, containing large volumes of snow. In contrast, the highest points of the detailed models are considerably lower (cf. Table I), resulting in a different importance of snow storage. Part of the differences found between the Ergolz and the other catchments can be explained from differences in snow storage during winter as well. The high degree of spatial variability of radiation and the role of temperature inversions inherent to mountain areas all affect snow melt and evapotranspiration, and therefore they were well represented in the detailed alpine models. This was not possible in the coarser RHINEFLOW model. Using monthly averages of temperature and precipitation in the RHINEFLOW model may occasionally result in different estimates of the amounts of snow storage and snowmelt. For example, when the average temperature in a month is below zero, RHINEFLOW stores all precipitation in that month as snow. However, if a cold month ends with a week of thaw and rain, the average temperature may be below zero, but there is runoff to the river.

The differences for the German Middle Mountains (Saar basin) seem to be caused by the representation of evapotranspiration processes (cf. Table II). Generally, the detailed models suggest an overall runoff decrease between 5% in winter and 25% in autumn, while the RHINEFLOW model suggests an increase in winter runoff and a much smaller decrease during summer. The concept of Thornthwaite used in the RHINEFLOW model to calculate evapotranspiration may have underestimated the effect of higher temperatures, and did not take the changes in air vapour pressure into account.

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 the 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.

In general, 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 sub-catchment can be different from the average situation in the larger area evaluated by the RHINEFLOW model. Examples are karst phenomena within the Ergolz catchment; large forest coverage in the Blies catchment; the importance of ground water storage in the flat sedimentary Vecht catchment.

6.2. COMPARISON OF DIFFERENT SCENARIOS

The greater changes observed for the UKHI scenario when compared to the XCCC scenario (Figure 2) are in agreement with the larger changes in the climate variables resulting from the UKHI experiment. The higher winter discharge according to the UKHI scenario is due to a higher temperature rise causing a larger reduction of snow storage, and a greater increase of winter precipitation. The lower summer flow under UKHI conditions is due to the smaller snowmelt contribution, and to a more intensified evapotranspiration due to the higher temperature rise and drier atmospheric conditions. Nevertheless, the trends of the responses are the same for both climate models.

6.3. ESTIMATION OF PEAK FLOWS

From the model results, it is difficult to achieve reliable estimates of peak flows under changed climate conditions. 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 simplified 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 may be 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.

Estimating effects in larger Alpine areas from the response in small catchments is a precarious task. Floods in larger catchments occur mainly in winter as result of large-scale frontal rainfall. In the Alpine area, a decrease in the number of flood days (discharge larger than the p95 fractile) is foreseen in summer, but an increase may occur in winter. Overall, a tendency to more contrasted streamflow regimes with more abundant winter flooding and summer flood due to convective storms seems to be produced. Annual peak flows with return periods of over 50 years may increase by about 10% until the year 2050.

Average discharge in the German Middle Mountains reduces due to accelerated evapotranspiration, and the model results suggest a reduction in the frequency of peak flows. Nevertheless, the magnitude of peak flows resulting from heavy rainfall and convective thunderstorms are expected to increase.

Since in winter both rainfall and the melt water runoff contribution from the Alps are expected to increase, peak flows in the middle and lower 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, based on the relationship between monthly average discharge and peak discharge, was applied to achieve estimates of peak flows in the downstream part of the Rhine basin (Kwadijk and Middelkoop, 1994). These estimates suggest that peak flows of the lower river Rhine with recurrence times in the order of 100 to 1000 years may increase by about 5–8% by the year 2050.

6.4. 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 biomass production as well as on the stomatal resistance and transpiration efficiency of the plant leaves require further attention. A reduction of low flows was found for all applied scenarios and in all catchments. In the Alpine catchments the decrease varied between about 10% and 30% for the XCCC2050 scenario and 20% to 40% for the UKHI2050 scenario. In the German Middle Mountains low flows decreased by about 10% under XCCC2050 conditions, and up to 20% under UKHI2050 conditions. In the lowland catchment the decrease of low flows was only a few percent. For the entire Rhine basin, summer low flows reduce by about 5% for the XCCC2050 scenario and 12% under conditions of the UKHI2050 scenario.

6.5. EVALUATION OF MODELS

The study provided valuable information on the pro’s and contra’s of the used types of models by experience. As mentioned before these are not in terms of ‘good’ and ‘bad’, but should be considered as a cost-benefit analysis. The detailed models could be well adapted to the catchment characteristics, such as the role of snowmelt, topography, evapotranspiration, and groundwater flow. The detailed models not only allow providing estimates of the changes in the averages, but also in the extremes. In addition, the models appeared valuable tools to understand in quantitative terms where and how climate change affects the hydrological cycle. These benefits, of course, have their price. The models have high data demands, which makes it difficult to build such models for large areas, or using long reference periods. In addition, the quality of the input data for the (changed) climate parameters should be accordingly fine, which is certainly not the case yet. Finally, it may be a precarious task to extrapolate the results obtained for small sub-catchments in different parts of a large river basin to a reliable quantitative estimate of the overall response of climate change on the scale of the entire basin.

The coarse RHINEFLOW model does enable such large-scale evaluations. Its simpler model concept has milder demands on data, which enabled us to develop it for a large basin, and using a long reference period. A version based on an 80 years reference period is available now. Moreover, the model scale is more in accordance with the resolution of the GCM results. The price here is paid in terms of the level of detail of the model. Its poorer conceptual representation of the hydrological processes may cause wrong estimates of snow melt, evapotranspiration or groundwater discharge on a local scale. Also, the coarse temporal resolution only yields estimates of average values.

Concern may arise in the justification of applying these models under changed climate conditions. In the validation runs, however, all models appeared robust for the present-day variability of climate (Grabs et al., 1997). Moreover, the physical base of key processes in the detailed models gives confidence that the models will provide reliable results under changed boundary conditions (climate, land use), though we realise that this cannot be proven by observations.

7. Impacts on Water Resources and Water Management

In spite of the uncertainties among the climate scenarios and applied models, the results indicate that changes in the discharge regime of the Rhine and its tributaries may already become apparent during the next decades. Winter discharge

TABLE IV

Mean number of days during the winter tourism period (Dec.–Apr.) in the Broye catchment for cross-country skiing (snow cover > 50 mm water equivalent) and alpine skiing (snow cover > 100 mm water equivalent) under present conditions and according to different climate change projections

	Present	XCCC2050	XCCC2100	UKHI2050	UKHI2100
Cross-country skiing					
Alt. range 900–1200 m	84	62	23	23	5
Alt. range 1200–1500 m	115	102	92	92	34
Alpine skiing					
Alt. range 900–1200 m	60	35	7	5	0
Alt. range 1200–1500 m	109	87	68	66	12

and peak flows are expected to increase, while summer discharge decreases, reducing water availability for various sectors. These changes can have considerable socio-economic implications. Several of these were considered.

7.1.1. *Winter Sport in the Alps*

Increased winter temperatures will reduce the spatial and temporal extent of the winter snow cover in the Swiss Alps (Bultot et al., 1994) (Figure 3a). This will reduce the length of the season for alpine and cross-country skiing, particularly in the zones below 1500 m a.s.l. Table IV shows the simulated reduction of the number of winter sports days for cross-country skiing and alpine skiing in the Swiss Broye catchment.

7.1.2. *Flood Defense*

The frequency and magnitude of peak flows is expected to increase. Due to the rise of the 0°-line in the Alps and the resulting degradation of the alpine permafrost, mass movements and rockslides may occur over larger areas. These may block the courses of mountain rivers, and thus form an additional cause of floods in these rivers. In the Alpine area peak flows may increase by over 10%. When no measures are taken this would imply a reduction of the current level of flood protection. In Switzerland, the following legally stipulated order of priority is observed in flood protection: (1) proper maintenance of watercourses, (2) land use planning measures, and (3) structural flood protection measures. Increased flood levels in the German part of the Rhine basin and along the course of the Rhine River raise the need of additional flood defense measures. These include the retention of water in the upstream parts of the basin, increasing the discharge capacity of the river channel, establishing an improved flood warning system, and raising the public awareness to floods (IKSR, 1995). Climate change may lead to an increase of the design discharge of the river dikes (which is the peak discharge with a 1250-year recurrence time) along the Rhine in the Netherlands by about 5–8% over the next 50 years. Here too, additional measures are demanded.

7.1.3. *Inland navigation*

An increased frequency of flood periods will stop inland navigation on the Rhine more often. Longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates. When the Rhine discharge drops below about 1000 to 1200 m^3/s, ships on the major transport route Rotterdam-Germany-Basle cannot be fully loaded, and transporting cost rise. The average annual number of days that the Rhine discharge at Lobith is below 1000 m^3/s may increase from 19 (under present day conditions) to 26 according to the XCCC2050 scenario and 34 according to the UKHI2050 scenario. Current projects on channel improvements can only partly alleviate these problems.

7.1.4. *Hydropower Generation*

Due to the increased winter discharge hydropower generation is expected to increase during this season. In Switzerland, the water availability for power generation may increase over the entire year, whilst further downstream the annual production decreases.

7.1.5. *Water Availability for Industry, Agriculture and Domestic Use*

Low flow periods during summer reduce water availability for industrial use and for drinking water production. During these periods the water demand for agriculture is expected to increase due to higher temperatures. Also, the use of river water for cooling purposes may be limited, not only because of a reduced river flow, but also because of higher water temperatures. In general, climate change will increase the water demand by various sectors, particularly during summer when water availability is low, and will require an even more balanced water-resources management.

7.1.6. *Floodplain Development*

Increase winter flooding will intensify the natural processes of inundation and sedimentation on the river’s floodplain, which is a desired development in view of ecological restoration. Periods of intensified water deficit and low river water levels, however, are unfavourable for wet ecosystems within the floodplain. Increased floodplain inundation may accelerate sedimentation rates, which over a time span of decennia may reduce the discharge capacity of the flood plain (Middelkoop, 1997).

8. Conclusions

The present study has provided a quantitative understanding of the impact of climate change on hydrological regimes in the Rhine basin. The combined top down/bottom up approach yielded detailed results for represented sub-catchments, as well as the overall effect for the entire basin. In this respect we could use the benefits of both modelling approaches. The obtained results were consistent, which gave confidence that they are a plausible estimate of the hydrological response of the applied climate scenarios.

Due to climate change the river Rhine is expected to shift from a combined rainfall-snowmelt regime to a more rainfall dominated regime. This coincides with a seasonal change in the discharge regime: winter discharge will increase, and summer discharges decrease. The frequency and height of peak flows will increase. The existing levels of safety will decrease. During summer, periods of low flow will occur more frequently and last longer. This will negatively affect water availability for domestic use, industry and agriculture as well as inland navigation, water quality and ecology.

The bandwidth of the simulation results is wide. This is primarily the result of uncertainty in the climate scenarios. A second concern is the way regional climate scenarios (in particular for precipitation) can be derived from downscaling GCM results. Different ways of downscaling the input climate scenarios might give different estimates of the changes. Finally, a minor part of the uncertainty is caused by disagreements among the model results.

In spite of the uncertainties, the results provide a sound basis for socio-economic impact assessment, as well as for the formulation of policy recommendations for river basin management. The implications for water management policy in the Rhine basin can be summarised as follows:

- The hydrological changes are expected to be so large that they should be considered explicitly in long term integrated river basin management. This includes policy fields such as spatial planning, environment and agriculture.
- The large uncertainty in the rate and magnitude of the changes, however, does not justify a policy of direct action. Instead, the appropriate management response here is to adopt the ‘no-regret and flexibility’ principle. Long-term plans and designs should be flexible and adaptable to changing insights on climate impacts. Anticipatory measures that serve different goals should be undertaken in combination with ongoing activities, such as the spatial ‘reservation’ of sufficiently large floodplain areas alongside the rivers in combination with ecological rehabilitation. ‘Wait and verify’ is not an appropriate strategy for sustainable river basin management. Once the changes become evident by ‘hard proof’, the financial means required for a short-term reactive response may overcharge the economic capacity of the riparian countries. It should be recognised in this respect that management and technical responses

to increased flood risk require a planning and implementation period of at least ten years.

The model results and the comparison of the different modelling approaches indicated that efforts to improve model results for the Rhine basin should focus on the following issues:

- A better quantification of the model results in terms of narrowing the uncertainty bands requires improvement of the climate change scenarios, in particular their spatial resolution, and their ability to provide reliable estimates of changes in precipitation amounts and intensity.
- The spatial and elevational complexity of the Alpine area and their effects on meteorological variables demands scenarios and models with a high spatial and temporal resolution for hydrological impact assessment.
- Changes in evapotranspiration play an important role in the estimates of low flows. For a sound estimation of future changes in evapotranspiration the effect of increased atmospheric CO_2 concentrations on the transpiration by vegetation should be better understood. In addition, the effect of land use changes and re-naturalisation should be further considered.
- The presently existing gap between the detailed models and the coarse RHINEFLOW model should be gradually bridged. Detailed models should be extended over larger areas, and RHINEFLOW should be refined. The first steps are already being taken: RIZA and BfG are developing detailed models (mainly aiming at modelling discharge peaks) for the German part of the Rhine basin. The RHINEFLOW-2 model with a 10-day basis and a 1 km × 1 km grid and with improved concept for calculating evapotranspiration has recently been built.

Future research on impact assessments should focus at integrated approaches, especially links between climate, hydrological and ecosystem models. Research should also aim at the evaluation of strategies to sustain and improve development of the river and its basin in a changing environment.

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References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., and Rasmussen, J.: 1986, 'An Introduction to the European Hydrological System – Système Hydrologique Européen, SHE, 1. History and philosophy of a physically-based, distributed modeling system', *J. Hydrol.* **87**, 45–59.

Anderson, E. A.: 1973, *National Weather Service River Forecast System – Snow Accumulation and Ablation Model*, National Oceanographic and Atmospheric Administration (NOAA), Tech. Mem., NWS-HYDRO-17, U.S. Department of Commerce, Silver Spring, MD.

Arnell, N. W.: 1992, 'Factors Controlling the Effects of Climate Change on River Flow Regimes in a Humid Temperate Environment', *J. Hydrol.* **132**, 321–277.

Arnell, N. W.: 1996, *Global Warming, River Flows and Water Resources*, Wiley, Chichester.

Arnell, N. W.: 1998, 'Climate Change and Water Resources in Britain', *Clim. Change* **39**, 83–110.

Bathurst, J. C. and O'Connell, P. E.: 1992, 'Future of Distributed Modelling: The Système Hydrologique Européen', *Hydrol. Proc.* **6**, 265–277.

Bergström, S.: 1976, *Development and Application of a Conceptual Runoff Model for Scandinavian Catchments*, Department of Water Resources Engineering, Lund Institute of Technology, Bulletin Series A 52, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

Bergström, S.: 1998, 'Requirements on Climate Scenarios for Water Resources Impact Studies – A Nordic Perspective', in *Proceedings of the Second International Conference on Climate and Water*, August 1998, Espoo – Finland, pp. 114–123.

Bergström, S. and Lindström, G.: 1998, 'A Swedish Perspective on Climate Change and Flood Risks', in *Second International RIBAMOD Workshop on Impact of Climate Change on Flooding and Sustainable River Management*, IH Wallingford, 26–27 February.

Beven, K. J.: 1989, 'Changing Ideas in Hydrology: The Case of Physical-based Models', *J. Hydrol.* **105**, 157–172.

Beven, K. J. and Kirkby, M. J.: 1979, 'A Physically Based Variable Contributing Area Model of Basin Hydrology', *Hydrol. Sci. Bull.* **24**, 43–69.

Beven, K. J., Kirby, M. J., Schofield, N., and Tagg, A. F.: 1984, 'Testing a Physically Based Flood Forecasting Model (TOPMODEL) for Three U.K. Catchments', *J. Hydrol.* **69**, 119–143.

Bicknell, B. R., Imhoff, J. C., Kittle, J. L., Donigian, A. S., and Johanson, R. C.: 1993, *Hydrological Simulation Program – Fortran (HSPF): Users Manual for Release 10*, U.S. EPA Environmental Research Laboratory, Athens, Georgia.

Bultot, F., Dupriez, G.L., and Gellens, D.: 1988, 'Estimated Regime of Energy-Balance Components, Evapotranspiration and Soil Moisture for a Drainage Basin the Case of a CO_2 Doubling', *Clim. Change* **12**, 39–56.

Bultot, F., Gellens, D., Schädler, B., and Spreafico, M.: 1994, 'Effects of Climate Change on Snow Accumulation and Melting in the Broye Catchment (Switzerland)', *Clim. Change* **28**, 339–363.

De Laat, P. J. M.: 1992, 'MUST, a Pseudo Steady-State Approach to Simulating Flow in Unsaturated Media', *ICID Bull. CIID* **41**, 49–60.

De Lange, W. J.: 1991, *A Groundwater Model of The Netherlands*, Rijkswaterstaat, RIZA nota 90.066.

Gellens, D. and Roulin, F.: 1998, 'Streamflow Response of Belgian Catchments to IPCC Climate Change Scenarios', *J. Hydrol.* **210**, 242–258.

Gleick, P. H.: 1987a, 'The Development and Testing of a Water Balance Model for Climate Impact Assessment: The Sacramento Basin', *Water Resour. Res.* **23**, 6, 1049–1061.

Gleick, P. H.: 1987b, 'Regional Hydrologic Consequences of Increases in Atmospheric CO_2 and Other Trace Gases', *Clim. Change* **10**, 137–161.

Grabs, W., Daamen, K., Gellens, D., Kwadijk, J. C. J., Lang, H., Middelkoop, H., Parmet, B. W. A. H., Schädler, B., Schulla, J., and Wilke, K.: 1997, *Impact of Climate Change on Hydrological Regimes and Water Resources Management in the Rhine Basin*, CHR-report I-16, CHR, Lelystad.

Gurts, J., Baltensweiler, A., Lang, H., Menzel., L., and Schulla., J.: 1997, *Auswirkungen von klimatischen Variationen auf Wasserhaushalt und Abfluss im Flussgebiet des Rheins*, Schlussbericht NFP 31, Zürich, Hochschulverlag AG.

Hulme, M., Conway, D., Brown, O., and Barrow, E.: 1994, *A 1961–1990 Baseline Climatology and Future Climate Change Scenarios for Great Britain and Europe. Part III: Climate Change Scenarios for Great Britain and Europe*, Climate Research Unit, University of East Anglia, Norwich.

IKSR: 1995, *Grundlagen und Strategie zum Aktionsplan Hochwasser*, IKSR, Koblenz.

IPCC: 1996, *Climate Change 1995; The Science of Climate Change*, Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), University Press, Cambridge.

Klemes, V.: 1986, 'Operational Testing of Hydrological Simulation Models', *Hydrol. Sci.* **31**, 13–24.

Kwadijk, J. C. J.: 1993, *The Impact of Climate Change on the Discharge of the River Rhine*, Ph.D. Thesis, Department of Physical Geography, Utrecht University, Netherlands Geographical Studies, 171.

Kwadijk, J. C. J. and Middelkoop, H.: 1994, 'Estimation of Climate Change on the Peak Discharge Probability of the River Rhine', *Clim. Change* **27**, 199–224.

Kwadijk, J. C. J. and Rotmans, J.: 1995, 'The Impact of Climate Change on the River Rhine: A Scenario Study', *Clim. Change* **30**, 397–425.

Lawford, R.: 1998, 'The GEWEX Continental-Scale International Project: Building a Bridge between Climate Science and Water Resources Management', in *Proceedings Second International Conference on Climate and Water*, August 1998, Espoo – Finland, pp. 124–138.

Leavesley, G. H.: 1994, 'Modeling the Effects of Climate Change on Water Resources - A Review', *Clim. Change* **28**, 159–177.

Liebscher, H.-J., Wilke, K., Krahe, P., Schultz, G., Schumann, A., Su, Z., Hamme, B., Funke, R., Hornbogen, M., Ott, M., Bardossy, A., and Plate, E.: 1995, *Entwicklung eines mathematischen Modells zur Untersuchung des Einflusses von Klima- und Landnutzungsänderungen auf den Hoch- und Niedrigwasserabfluß im Einzugsgebiet der Mosel sowie Echtzeitvorhersage unter Verwendung von Fernerkundungstechniken*, UBA Forschungsbericht Wasser 102 01 304, Bundesanstalt für Gewässerkunde Koblenz und Ruhruniversität Bochum, Lehrstuhl für Hydrologie, Wasserwirtschaft und Umwelttechnik Bochum.

Middelkoop, H.: 1997, *Embanked Floodplains in The Netherlands. Geomorphological Evolution over Various Time Scales*, Ph.D. Thesis, Department of Physical Geography, Utrecht University, Netherlands Geographical Studies, 224.

Mimikou, M., Kouvopoulos, Y., Cavadias, G., and Vayianos, N.: 1991, 'Regional Hydrological Effects of Climate Change', *J. Hydrol.* **125**, 221–241.

Mortsch, L. D.: 1998, 'Assessing the Impact of Climate Change on the Great Lakes Shoreline Wetlands', *Clim. Change* **40**, 391–416.

Panagoulia, D.: 1992, 'Impacts of GISS-modelled Climate Changes on Catchment Hydrology', *Hydrol. Sci.* **37**, 141–163.

Parmet, B. W. A. H., Kwadijk, J. C. J., and Raak, M.: 1995, 'Impact of Climate Change on the Discharge of the River Rhine', in Zwerver, S., Van Rompaey, R. S. A. R., Kok, M. T. J., and Berk, M. M. (eds.), *Climate Change Research. Evaluations and Policy Implications, Proceedings of the International Climate Change Conference*, December 1995, Maastricht, The Netherlands, Studies in Environmental Science 65B, Elsevier, Amsterdam, pp. 911–918.

Santer, B. D., Wigley, T. M. L., Schlesinger, M. E., and Mitchell, J. F. B.: 1990, *Developing Climate Scenarios from Equilibrium GCM Results*, Max Planck Institut für Meteorologie, Report 47, Hamburg.

Van Deursen, W. P. A. and Kwadijk, J. C. J.: 1993, 'Rhineflow: An Integrated GIS Water Balance Model for the River Rhine', in Kovar, K. and Nachtnebel, H. P. (eds.), *Application of Geo-*

graphic Information Systems in Hydrology and Water Resources Management, Proceedings of the Conference on HYDROGIS, Vienna, Austria, IHAS publication 211, pp. 507–519.

Warmerdam, P. M. M., Kole, J. W., and Stricker, J. N. M.: 1993, ‘Rainfall-Runoff Modelling in the Research Area of the Hupselse Beek, The Netherlands’, in *Proceedings of the International Symposium on Runoff and Sediment Yield Modelling*, Warsaw, 1993.

Wigley, T. M. L. and Raper, S. C. B.: 1992, Implications for Climate and Sea Level of Revised IPCC Emission Scenarios, *Nature* **357**, 293–300.

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