Climate Change Research: Evaluation and Policy Implications
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ASSESSMENT REPORT ON NRP SUBTHEME

"REGIONAL HYDROLOGY"

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ABSTRACT

The major part of the Netherlands consists of a low-lying river delta which is very sensitive to hydrological conditions in the North-Western part of the European continent. The rivers Rhine, Meuse and Scheldt carry through this delta to the North Sea annually nearly 100 km^3 of fresh water. This water originates from a drainage basin of about 185 000 km^2, which is 6 times the country area. The present geography of the Netherlands has largely been shaped by this river inflow and by the sediments which are carried along. Interaction of these fluxes with North Sea hydrodynamics in a period of rising sea level has produced large lowlands, which in the past millennium have been reclaimed for agricultural, urban and industrial purposes. At present an extended hydrological infrastructure is required to contain high waters and to keep ground water and surface water tables permanently under control. Otherwise more than half of the Netherlands would be permanently or frequently flooded.

In the Netherlands water management is a matter of permanent concern. The abundance of water is at the same time source of prosperity and source of vulnerability. Waterways for shipping and water supply for agriculture, industry and domestic use are essential resources for economy. The Dutch wetlands also represent a great environmental value. Changes in water supply and river discharge therefore have important impacts. More frequent occurrence of low discharge is detrimental to fluvial transport and agriculture. More frequent occurrence of high river discharge affects the safety of population against flooding and causes economical damage. Additional sedimentation raises the river beds with respect to the surrounding lowlands with possible consequences for safety and river management.

The previous considerations form the basis for the sub-theme “REGIONAL HYDROLOGY” of the Dutch climate change research programme NRP. Seven research projects dealing with different aspects of the hydrological system have been selected in order to study the vulnerability of the Netherlands to climate related hydrological change. Although not all components of the hydrological system could be studied, the most important processes and relationships in the hydrological system have been addressed (see Figure 1). In the present phase of research most of the results still have an indicative character. Some projects have been completed, but others have started only recently. Nevertheless several important conclusions already emerge, which are summarized below:

- Recent scenarios indicate greater regional climate changes than assumed in the past. Most remarkable are the strong expected increase in winter precipitation and the increased drought in summer.
- With increasing CO_2 concentrations forests will become more resistant to droughts. If biomass does not increase, the evapotranspiration will decrease, causing an increase in drainage to ground water and run-off.
- Drought damage to crop production will increase. Agriculture will be less affected in the low lying river delta than in neighbouring regions. This may yield a comparative advantage for the Dutch economy.
- In coastal lowlands no substantial increase in saline seepage is expected, even if the sea level rises more than one meter.
- The discharge regime of the Rhine will change drastically. The annual variability of the discharge will strongly increase; winter discharges will increase and summer discharges will decrease.
- Periods of low river discharge will become more frequent and more prolonged. This will diminish the transport function of the Rhine, with serious economic consequences. The availability of cooling water for power plants will also be affected. A shortage of Rhine water will cause further intrusion of saline water in the lower river delta.
- The frequency of high discharges will increase. This causes more frequent inundation of the embanked floodplains in the Netherlands. It is not yet clear to what extent this will change safety from flooding.
- Sensitivity of soils to erosion is more affected by the expected changes in land use than by climate change. The production of sediment by soil erosion may be substantially increased by changes in precipitation.
- Sedimentation rates on the embanked floodplains in the Netherlands will increase. As a consequence, polluted sediments will become an increasing environmental concern. Pollution in the catchment basins of Rhine, Meuse and Scheldt has to be kept under control.

A general conclusion from the different sub-theme studies is that the most serious impacts of climate change result from a shift in extreme conditions more than from a shift in average climate conditions. At present no reliable indications can be given regarding changes in frequency of extreme conditions. This question should be addressed with priority in the future NRP. It appears that, in particular, a more frequent occurrence of periods of drought will have significant economical consequences.

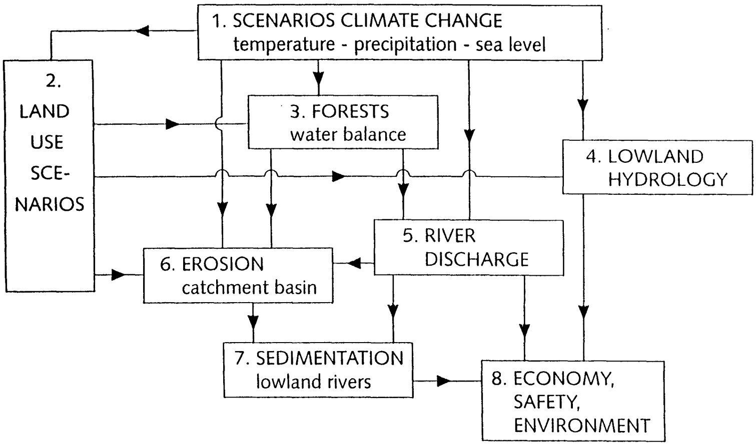

Figure 1.1
Structure of NRP subtheme Regional Hydrology and flow-chart of climate change impacts through Regional Hydrology

1. INTRODUCTION

Climate change is the driving force in a chain of processes which by altering the hydrology of the Netherlands affect important economical and social values. Changes in temperature and precipitation/evapotranspiration in the catchment basin of the rivers Rhine, Meuse and Scheldt and changes in sea level will affect the water and sediment balances of the Dutch coastal lowlands. Change in land use should also be taken into account. Change in land use may occur in response to climatic factors, but also in response to social or economic factors. Changes in climate and land use both affect the retention capacity and evapotranspiration of the catchment basins and by this the variability of water supply and river discharge. There is also an impact on soil erosion and sediment loading of the rivers with possible consequences for river management.

Climate related change of regional hydrology therefore has an important impact on The Netherlands, physically, economically, socially and environmentally. This leads to the questions:

Are the hydrological infrastructure and water management practices in the Netherlands adequate for coping with climate change?

Which adaptation measures could be considered?

The chain of hydrological processes by which climate change affects socio-economic and environmental values is depicted in the scheme. This scheme forms the structure of the sub-theme Regional Hydrology. Each process in the chain has been addressed by a specific NRP-project. Starting point are *scenarios for relevant climate related variables*. Different scenarios are considered, each representing an internally consistent set of projections of global climate change at the regional scale. They form basic input for the different research projects within the sub-theme. Much attention has been paid to the consistency of scenario assumptions used in the different projects. To the climate change scenarios are added *scenarios for change in land use*. Changes in *soil erosion* and *river discharge* are studied as primary consequences of the climate and land use scenarios. A special underlying study is devoted to the *water balance of forest areas*. Another special study deals with the *water balance of lowlands* which are affected by salt water seepage and sea level rise. As a secondary consequence of climate and land use change the *sedimentation in the lowland river system* is investigated. Change in river morphology lags behind the aforementioned processes and therefore is a concern for the longer term. In a final chapter some indications are presented with respect to the *economic, social and environmental consequences* of the impacts of climate change through the hydrological system.

The results obtained sofar in the sub-theme Regional Hydrology do not yet cover the complete hydrological system of the Netherlands including all its catchment basins. Ground water has not been dealt with in a general way; only for a particular type of lowland areas the ground water balance has been studied. Impacts of climate change on the coastal marine system are not considered in the sub-theme.

Table 1.1
List of projects in the subtheme "Regional Hydrology"

Title	Project leader	Number
Impact of climate change on the discharge of the river Rhine	B.W.A.H. Parmet	850001
Influence of climate change on the sedimentation of the rivers Rhine and Meuse (embanked floodplains)	H.J.A. Berendsen	850002
Effect of increase of CO_2 on the balance of the forested landsurface	A.W.L. Veen	850015
Effect of climate change on groundwater and surface hydrology in the low-cosastal regions of The Netherlands	P. Kabat/ L.C.P.M. Stuyt	851041
The effects of climate change on transport and sedimentation of suspended load of Rhine/Meuse	H.J.A. Berendsen	851059
The impact of temperature and rainfall changes on land degradation in source areas of the suspended sediment load of the Rhine	F.J.P.M. Kwaad/ A.C. Imeson	852089

2. CLIMATE SCENARIOS

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2.1 Introduction

Climate impact studies require knowledge of the evolution of climate variables on scales ranging from local to global. Of particular importance in many studies are variables like mean precipitation and its variability, sometimes down to timescales of one day or less. The present-day GCM simulations are still unable to produce reliable predictions for these. One reason for this is the coarse spatial resolution of the models in comparison which the typical size of precipitation areas, which prevents the inclusion of a physically correct description of precipitation; another reason is the present incapability to represent the large-scale atmospheric flow correctly enough to estimate from it even the large-scale precipitation, which depends essentially on the first derivative of the gradient in the flow pattern.
To fill this gap, climate scenarios can be constructed. They can be defined as follows (Viner and Hulme 1993) : " A climate scenario is an internally consistent representation of a possible future climate [...], that can be used to get a better understanding of the consequences of climate change [...]".

2.2 The need for standardization of scenarios within NRP

Integration of results of impact studies requires a certain level of standardization of climate scenarios, particularly because different effects may be sensitive to different climate variables, or even to a combination of such variables. Among such variables are means, variances, autocorrelations and extremes of elements like temperature, precipitation, radiation, evaporation and so on. For hydrological studies, precipitation is a key variable. Due to the reasons mentioned before, direct GCM-prediction can not be used. A common approach to obtain absolute values of monthly means is to apply the relative change in precipitation, as obtained from GCMs for a future climate to the observed monthly means (Bultot 1988, Kwadijk 1993); an evolution in time is then obtained by scaling of the change with the GCM-predicted global temperature change. This procedure preserves in first order the internal consistency of the precipitation-global temperature relation. To obtain a scenario on e.g. daily time scale, an observed daily time series might be transformed into a time series for a future climate, just by scaling all daily values with the relative difference in monthly means. However, it is not a priori guaranteed that such a procedure results in a scenario that is meteorologically consistent and hence in e.g. realistic extremes.

2.3 The KNMI approach to precipitation scenarios

In the KNMI method, it was attempted to produce precipitation scenarios in the form of daily time series that can be considered to be representative for a future climate. These time series are obtained by transformation of an observed daily time series of temperature (T) and precipitation (RR). If required, a scenario for monthly means follows immediately from the averages of the transformed time series.

The transformation is done as follows. First, a season-dependent change in temperature is applied to all observed daily temperatures T in the series. The magnitude of the change is based on GCM information. This leads to a new series of temperature T*. Then, the daily precipitation amounts RR are changed. This is done on the bases of the observed relation between RR and T in the present climate (Figure 2.1) on wet days (threshold 0.1 mm/day), rather than on bases of GCM-information. The data were fitted by the following piecewise polynomical function R(T) with Temperature in Celsius degrees and daily Rainfall in mm).

$$R(T) = \exp[0.76 + 0.083\,T] \qquad T \le 7^\circ$$
$$R(T) = \exp[0.76+0.083\,T-0.014\,(T-7)^2+ 0.0007\,(T-7)^3] \qquad T \ge 7^\circ \text{ and } T \le 21^\circ \qquad \text{Eg. 1.}$$
$$R(T) = \exp[-0.47+0.103\,T] \qquad T \ge 21^\circ (1)$$

and the transformed precipitation RR* in the series were obtained by applying to the observed amounts each day a factor F that depends on T and T* :
$RR^* = [R(T^*) / R(T)]\, RR = F \,.\, RR (2)$

This scenario, referred to as KNMI-1, assumes implicitly that the mean T-RR relation remains in first approximation preserved in a changing climate.

Table 2.1 shows the dependence of F on T and T* for T* - T= 3°C. We note that the coefficient of variation (standard deviation divided by the mean) of the original series and the transformed one is the same. The plausibility of such a result is supported by the fact that the coefficient of variation of RR shows no clear dependence on temperature.

Table 2.1
Multiplying factor F for various values of temperature T when there is a constant increase in temperature of 3°C on every day (T*=T+3°C). The standard error of F is given in parentheses

T	T*	F	
-12	-9	1.28	(.02)
:	:	:	:
4	7	1.28	(.02)
6	9	1.21	(.01)
8	11	1.08	(.01)
10	13	.98	(.01)
12	15	.95	(.01)
14	17	.96	(.02)
16	19	1.02	(.03)
18	21	1.14	(.06)
20	23	1.26	(.09)
22	25	1.28	(.10)
24	27	1.28	(.10)

A second scenario, KNMI-2, assumes that the R-P-T relation is in first approximation constant, where P is surface air pressure. This leads to the application of a R-T relation that is explicitly pressure dependent. An additional assumption of KNMI-2 is that the difference in pressure is taken to be zero. This is analogous to the assumption that in first approximation the circulation remains unchanged in a future climate. We note, that this assumption does not apply to KNMI-1, as there is an implicit variation of P with T present in Figure 2.1 according to the present-day climatology.
Table 2.2 compares the KNMI scenarios for seasonal means with other sources. The T^* - T are taken from the Canadian Climate Centre GCM-model. The Bultot and Kwadijk scenario are based on direct model output of GCMs. In general, there is agreement between the various methods, apart from the summer. The latter is probably related to the absence of an accurate description of convective precipitation in the GCMs, which in our method is described by the right hand part in Figure 2.1.

The scenarios can be based on the R - T_{max} relation too, in which T_{max} is the daily maximum temperature. This leads to other constants in Eq. 1. For further details of he various scenarios we refer to Klein Tank and Buishand (1993a; 1993b; 1994) and Buishand and Klein Tank (1994).

Although the KNMI scenarios can give a plausible description of the variability of rain and temperature down to very short time scales, its spatial validity is restricted. Over an area of the Netherlands inland the R - T relations are similar, so that a de Bilt-based scenario can be applied in that region. It is presumely also valid in the German lowlands. Extension to other areas like the middle and south basin of the Rhine requires analysis of the R - T relation in those regions.

Table 2.2
Mean seasonal changes ($2^* CO_2 - 1^* CO_2$) in temperature T (°C) and precipitation R (%) in 2 KNMI climate scenarios for the Netherlands. The values are compared to model predictions of the Canadian Climate Centre GCM (Boer et al., 1992; McFarlane et al., 1992) and the scenarios used by Bultot et al. (1988) and Kwadijk (1993)

		Season				Year
		DJF	MAM	JJA	SON	
ΔT (°C)						
KNMI-1,2 1)		+ 3.0	+ 2.3	+ 3.7	+ 3.4	+ 3.7
CCC-GCM 2)		+ 3.0	+ 2.3	+ 3.7	+ 3.4	+ 3.7
Bultot 3)		+ 3.2	+ 3.1	+ 2.5	+ 2.7	+ 2.9
Kwadijk 4)	High	+ 5.7		+ 4.3		+ 5.0
	Best	+ 4.3		+ 2.7		+ 3.5
	Low	+ 3.2		+ 1.7		+ 2.5
ΔR/R (%)						
KNMI-1,5)		+ 20	+ 8	+ 6	+ 5	+ 10
KNMI-2 5)		+ 19	+ 10	+ 10	+ 10	+ 12
CCC-GCM 2)		+ 28	+ 21	- 26	- 11	+ 2
Bultot 3)		+ 15	+ 11	- 10	+ 6	+ 7
Kwadijk 4)	High	+ 34		+ 25		+ 32
	Best	+ 19		+ 4		+ 11
	Low	+ 4		- 20		- 10

1) Taken from the CCC-GCM. (see 2))

2) Changes predicted by the CCC-GCM; T values are for 16 landgridpoints surrounding the Netherlands whereas R values are for 2 landgridpoints covering the Netherlands; two other high resolution GCMs (Geophysical Fluids Dynamics Laboratory GFHI and United Kingdom Meteorological Office UKHI) show somewhat higher temperature increases: about +5°C (Houghton et al., 1992).

3) Three monthly values of the Bultot scenario are averaged. The scenario is valid for Belgium and compiled from various early-GCM sources (Manabe and Stouffer, 1980; Manabe et al., 1981; Washington and Meehl, 1983).

4) Scenario based on monthly mean changes predicted by the ESCAPE model for gridpoints covering the northern part of the Rhine-basin (using the IMAGE and STAGGER climate modules in ESCAPE; Rotmans, 1990; Wigley et al., 1991). The values presented are for the IPCC Business-as-Usual emission scenario (BaU). High, Best and Low denote upper 90% confidence limit, mean and lower

90% confidence limit of temperature and precipitation changes obtained with 6 different GCMs.

5) A temperature-dependent multiplying factor is applied to each individual rainday in the record at De Bilt (1961-1990).
For KNMI-1 this factor is derived from the observed precipitation-temperature relation on wet days at De Bilt (1906-1981) as presented in Figure 2.1. The factor represents the relative change in the mean daily precipitation amount given a certain temperature perturbation ΔT; it ranges from 0.9 for days with T≈12°C to 1.3 for days with T below 4°C and T above 21°C. KNMI-1 implicitly assumes that the surface air pressure P changes according to the present-day relation between P and T.
For KNMI-2 this factor is derived from the observed precipitation - temperature/surface air pressure relation on wet days at De Bilt (1906-1981). The factor represents the relative change in the mean daily precipitation amount at distinct values of surface air pressure P given a certain temperature perturbation ΔT; it ranges from 0.7 for days with T≈17°C and P≈1000 hPa to values > 2 at low and high temperatures. KNMI-2 explicitly keeps the daily surface air pressure P unchanged.

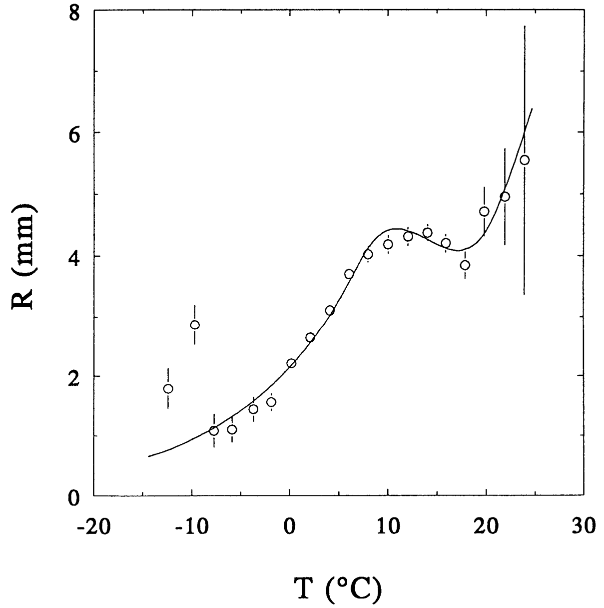

Figure 2.1
Mean precipitation amounts at temperature T class intervals of 2°C for wet days (threshold 0.1 mm) at De Bilt (1906-1981). The figure is based on 15897 wet days (57% of the total number of days). The number of wet days in a temperature interval is 2104 for the T= 6°C class and decreases to about 10 at the extreme temperatures. The error bars indicate the estimated standard deviations of the means. The smooth curve represents the fitted regression relation (Equation 1)

2.4 Conclusions

Precipitation scenarios with a time resolution of one day can be obtained from the empirical relation between observed precipitation amounts and temperature. The corresponding change in seasonal precipitation compares well with GCM-based scenarios, apart from the summer.

The scenario can be refined by taking pressure into account as predictor, to account for systematic changes in circulation in case there are clear indications of these in GCM output.

The scenarios obtained in these ways are meteorological consistent and provide a plausible description of extremes. Extension to other regions in Europe requires study of the local time series to find the geographical dependence in the results of Eq. 1.

3. LAND USE SCENARIOS

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Abstract

Land use is an important parameter in hydrological and morphological processes. Climate change can induce changes in land use because the production and water use of crops is influenced. In the framework of a project of the International Commission for the Hydrology of the Rhine Basin, land use scenarios have been developed for the Rhine area. Besides climate change, autonomous developments were taken into account, since these determine for a major part the land use changes. A biophysical classification system has been designed and in combination with a crop simulation model geo-referenced information on land use potentials under present and possible future conditions is generated. The influence of climate change is mainly positive, the production increases. Autonomous developments were expressed in a Central Projection with a Plus and a Minus variant. In the Central Projection about one million hectare (10%) is vacated and comes available for other purposes than agriculture or urban land. In the Minus variant this is 3 million and in the Plus variant zero. Changed climate adds 0.2 million hectare to this, because less land is required due to the higher production.

3.1 Introduction

Land use determines interception of precipitation, influences the ratio between infiltration and surface runoff and determines to a large extent the evapotranspiration. It is therefore an important parameter in hydrological and morphological processes. An increased CO_2-content and associated climate change might induce changes in land use, since growth and evapotranspiration of plants are influenced, see also Section 4 and 5. For natural vegetation this could mean that existing ecosystems move, alter in their species composition or even completely disappear. For agricultural crops the most important aspect is that crop production may increase. Furthermore cropping patterns can change and new varieties can be introduced, that cannot be grown under present climate conditions. Whether changed climate conditions lead to changes in land use as described above, depends for a major part on economic, political, demographic and technical, socalled autonomous developments. As there are large uncertainties, both with respect to climate change and to autonomous developments, possible changes in land use have to be expressed in alternative scenarios.

In the project 'Influence of climate change on the discharge of the river Rhine', that is coordinated by the International Commission for the Hydrology of the Rhine Basin (CHR), also the effects of land use changes are considered. Land use scenarios taking into account the effects of climate change in combination with autonomous developments were not available and have been developed as part of the CHR-project. The study has been carried out by the Winand Staring Centre at the request of The Institute of Inland Water Management and Waste Water Treatment. In this chapter the methodology and the results of the study are presented.

3.2 Method

To determine the possible impacts of climate change on crop production a preliminary study was carried out (Wolf en van Diepen, 1991). The study showed that the effects of a doubling of the CO_2-concentration and an increase in temperature are mainly positive. Most crops grown in Western Europe are of the socalled C3 type, for which the CO_2-concentration is sub-optimal. An increase in CO_2 acts as a fertilizer and the assimilation rate increases. For socalled C4 crops, of which maize is the only important representative, the CO_2-concentration is optimal and the increase in assimilation rate does not occur. An increase in temperature enhances the CO_2 growth stimulation and increases production where temperature conditions are sub-optimal. Besides production, CO_2 influences the water use efficiency. With higher CO_2-concentrations, the stomata of crops have to be opened less to take up the same ammount of CO_2. The water loss per stomata is less. For the overall water use of crops the increase in production counterbalances for a part the increase in water use efficiency, because the leaf surface increases.

An important conclusion of the preliminary study is that more CO_2, an increase in temperature and a small change in precipitation during the growing season, does not bring about limitations and even improves the circumstances for the cultivation of presently grown crops. Moreover possibilities for other crops arise. Climate change itself will however not directly generate changes in land use in the Rhine Basin. Although the changed climate boundary conditions will play a role, land use changes will be determined by autonomous developments. A farmer will only grow another crop if it is economically more profitable. It follows that the autonomous developments are very important with respect to changes in land use. The study to land use scenarios for the Rhine basin was therefore divided in two parts. A biophysical and a socio-economic part. The target period is around the mid of next century when, according to the Business as Usual emission scenario of IPCC, the CO_2-concentration has doubled. A best guess climate scenario for this period was derived from Kwadijk (1993). The scenario assumes an increase in temperature of 1.5°C in summer and 2°C in winter. Precipitation remains unchanged during summer and increases with 10% during winter.

The biophysical part is aimed at assessing the effects of a doubling of the CO_2-concentration and a changed climate on crop production, crop water use and cropping calendar (Roetter, 1994; Roetter en van Diepen, 1994). The specific aim is to give geo-referenced information on land use potentials under present and possible future conditions. To cover the regional differences in climate and soil in the Rhine basin, a biophysical classification system has been developed. The changes in potential (optimal supply of water, nutrients and pesticides) and water limited yields (optimal use of nutrients and pesticides) and water use of agricultural crops have been investigated using a crop growth simulation model. Simulation results for present and possible future climate were combined into changes in land suitability and attainable yields in the Rhine Basin.

The socio-economic part examines the influence of autonomous developments on land use and combines this with the results from the biophysical part into scenarios or projections (Veeneklaas et al, 1994). A Central Projection describes the long-term tendency in land use and is based on secular historic trends, fundamental scientific and technical principles and basic assumptions. Secular trends have been used to underpin quantitative statements about future developments. Scientific and technical restrictions refer mainly to attainable agricultural production levels and land suitability and follow from the biophysical part. The basic assumptions are the most controversial. By referring to other studies on future developments they can be made plausible to a greater or lesser degree. In case of great uncertainty a Plus variant and a Minus variant is constructed. For the Plus variant maximum, and for the Minus variant minimum urban and agricultural claims on land are assumed. The socio-economic part results in two types of land use projections. For unchanged and changed conditions a Central Projection is constructed with, if necessary a Plus and a Minus variant.

3.3 Results

Biophysical part; changes in land use potentials

A biophysical classification system containing the elements climate and soils and adapted for present and possible future conditions was not available for the Rhine basin and had to be developed. First a bioclimatic classification was designed, which was combined with a soil classification and integrated in a Geographical Information System (GIS) (Roetter, 1994).

Climatic, agroclimatic and agroecological maps show that annual mean temperature, precipitation and annual temperature amplitude are the main factors to describe the regional differentiation of agricultural crops and natural vegetation. The bioclimatic classification system was based on meteorological data for 53 stations and a digitized altitude map. Regression equations were derived between meteorological variables as dependent variables and combinations of altitude, longitude and latitude as independent variables. Based on the regression analysis and known classification systems the set-up of the bioclimatic system for the Rhine basin is based on:

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).

The first three levels are based on regression equations and the fourth level is based on a digitized precipitation map. The equations have been derived both for present and possible future conditions. They are implemented in a GIS and consequently bioclimatic data surfaces can be easily obtained. In total 700 combinations are possible, but only 90 occur at present in the Rhine Basin of which 25 have a surface area larger than 1%. With the assumed scenario, the climate becomes more maritime/less continental and warmer.

The soil suitability classification was based on a digitized soil map. Soil mapping units were clustered in four soil suitability groups based among others on slope class, soil texture, depth, moisture retention characteristics and soil genesis. Biophysical types were generated with the GIS by combining the bioclimatic types with soil suitability groups. This was done for present and possible future conditions. It has been assumed that a change in climate does not affect the soil characteristics used in defining suitability groups.

With the crop growth model WOFOST, potential and water-limited yields have been 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 en van Diepen, 1994). Computations were carried out with 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. The crop characteristics were adapted for future conditions according to state of the art knowledge. In line with the preliminary study, the simulations with WOFOST showed that, in general, production increases. Under water-limited situations, besides the CO_2-fertilizer effect, the increased water use efficiency causes the production to increase. For the group of soils with an available water capacity of 70 mm, the average production for the Rhine area increased for winter wheat with 40%, of rye-grass with 33%, of sugar beets with 25% and of silage maize with 12%.

It can be derived from the simulations that soil and terrain characteristics in combination with a change in mean annual temperature are the main determining factors with respect to land suitability. Based on these criteria, five land suitability classes were defined: Very high, high, moderate, marginal and unsuitable. If climate changes according to the described best guess scenario, the areal percentages of land suitability classes change as described in table 3.1. The class "very high" increases from 1.3 to 38.6%. The percentages of the other classes decrease. The assumed climate change has a positive effect on the overall suitability of land for cultivation of current crops and tree species.

Socio-economic part; land use projections

Starting point for the land use projections is the present land use in the Rhine basin. The Rhine basin has been divided into 13 regions based on the NUTS-1 division of the European Union (EU). Land use was derived from statistics. Half of the total area of the Rhine basin is used for agriculture and about one third is covered with forest. The basin is densely populated with about 55 million people, consequently a relatively large share, 11%, is built-up land.
The Central Projection is based on secular trends in the past, other surveys of the future and basic assumptions including technical and scientific restrictions

(Veeneklaas et al., 1994). Looking at past secular trends in land use, it seems that we enter a period of contraction of the agricultural area. This is founded on the ongoing productivity increases and stagnating demand following from the low expected population growth. Furthermore, there are many parallels with other historic periods of contraction. A decline in agricultural area is also the outcome of other surveys of future land use. The rate of decline in these surveys depends on the scenario assumptions, for example free trade versus protected markets.

Table 3.1
Areal percentages of land suitability classes for unchanged and changed climate conditions (Roetter en van Diepen, 1994)

Land 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

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, although at a slower rate than during the last 40 years. For agriculture it is assumed that technical progress will go on and that regional differences in ratio between actual and water limited production will level out. Around the mid of next century 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. Because food remains a strategic good a completely free market will not develop. Consequently, world trade in agricultural products will not expand dramatically and protection of own markets for food will not disappear. For agricultural production stricter environmental regulations are expected, which will however not prevent approaching the water-limited yields. Furthermore it is assumed that in the long run there will be a tendency to grow crops in those parts of the Rhine Basin that have the highest yields. A certain degree of diversification within the regions will however remain.

To construct the projections a hierarchical scheme is 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 the 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 is nested, based on the profitability and the required quality of land; Horticulture and permanent crops, root crops, cereals and, with the lowest priority, grassland and fodder crops.

For the Rhine basin as a whole the changes are listed in table 3.2. The basic assumptions of the Central Projection result in an increase in urban land use. The

Plus variant assumes an increased population growth and more urban sprawl and results in a larger increase of urban land use. In the Minus variant it decreases because of a decrease in population and lower land claims per inhabitant. Nature conservation claimed by policy plans has the same position in the hierarchy as urban land use. In the Netherlands explicit claims have been formulated in the Nature Policy Plan of about 10% of the agricultural area.

The area used for agriculture decreases in all projections. With changed climate conditions this decrease is even larger, because production levels increase and hence, less land is needed. The main decrease is found for cereals. Outside the EU production costs are lower and furthermore the physical production conditions of the Rhine basin within the EU are not optimal for cereal production. The production will therefore partly shift to outside the Rhine Basin. Next in line are potatoes. For this crop strong competition is expected with Eastern Europe. Only for beets a small increase in area is expected for the Central Projection and the Plus Variant, for unchanged climate. This is mainly caused by an increase in the production of fodder beets, that will be used in cattle feed in line with a development of more self-sufficiency in dairy farming.

The changes in area of urban and agricultural land use can differ for the 13 distinguished regions. For the region Nederland-Oost (Netherlands-East) for example urban land use increases with 37% in the Central Projection. If nature reserves are included the increase is 72%. Agriculture decreases with 16% for unchanged and with 21% for changed climate conditions. In the Minus variant the agricultural land use decreases with 35%. Besides grassland, the acreage of cereals and potato decreases.

Table 3.2
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 decade 2040-2050, in million ha and percentages (Veeneklaas et al., 1994)

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

In the Central Projection about one million hectare would become available for other use, in the Minus variant this is 3 million hectare and in the Plus variant no substantial surplus would be available. Changed climate conditions add approximately 0.2 million hectare. In Germany and the French part of the Rhine basin large parts will be vacated, mainly the areas were presently cereals are grown. The vacated areas could be used for afforestation, especially if different functions like timber production, recreation and nature can be combined. Other plausible possibilities are nature reserves or mixed designation, like dispersed housing, hobby farming, etc. The production of industrial crops does not require large amounts of land and biofuel production is economically not viable. These are therefore less realistic options for the vacated land.

3.4 Implications

A doubling of the CO_2-content and an increase in temperature seem to have a positive influence on crop production. The implications of a climate change as assumed in this study are however small for land use, compared to the influence of autonomous changes. In general, also without climate change, it may be expected that the area built-up land will increase but the agricultural area will decrease at a faster rate. This may offer possibilities for nature development and afforestation. Possible implications for morphological processes in the Rhine basin are briefly discussed in Sections 7 and 8 and for hydrological processes in 6.

It should be noted that in this study only average changes in climate were considered. Changes in for example frost risk or extreme events such as hail storms have probably a larger influence on average yields and yield variability and consequently on land use. However, due to lack of information on changes in these phenomena, they were not taken into account.

4. FORESTS

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Abstract

The possible impact of an increase in CO_2 on the hydrology of forests is evaluated using sensitivity analysis and a climate scenario on an one-dimensional model of forest hydrology. Water use of forests is affected by plant physiological and meteorological variables. Doubling of CO_2 leads to a decrease of stomatal conductance, resulting in a decrease in transpiration of 10 to 30%. The evaporation of rainfall interception by the canopy is increased due to a higher leaf area index and higher temperatures. Total interception increases, but the ratio between interception and precipitation decreases. Simulating a small increase in forest canopy increases the evapotranspiration only weakly and the higher precipitation in the scenario is mainly passed on to drainage. Drought damage in summer should reduce, but winter discharge may strongly increase.

4.1 Introduction

A change in the concentration of CO_2 as well as a possible climate change will have direct and indirect effects on the water use of plants, including trees. The changing concentration of ambient CO_2 directly effects physiological processes in the plant. The indirect effect results from the change in meteorological variables. Forests are aerodynamically rough and are therefore strongly coupled to atmospheric conditions. As a result, changes in the atmosphere might affect forests stronger than other vegetation types.

The aim of this study is to estimate the consequences of a climatic change associated with a doubling of the atmospheric CO_2 concentration, for the water balance of forests. The results may be used in other studies in the subtheme Regional Hydrology. Given the direct effect of CO_2 on plant physiology, the project is also part of subtheme Terrestrial Ecosystems.

The water flow in forests can be divided into interception of rainfall, transpiration by the canopy and drainage to groundwater. Interception and transpiration depend on meteorological variables and characteristics of the canopy. Transpiration is regulated by the stomatal conductance. Because of the turbulent flow of air in the canopy the dependency of interception and transpiration on meteorological conditions is much stronger for forests than for low vegetation. Soil characteristics determine in general the availability of water and the rate of drainage.

A simultaneous change in atmospheric CO_2 concentration and in climate influences the forest ecosystem in a complex way. Photosynthesis, water use efficiency, growth, canopy structure, nutrient circulation, species composition and phenology are all affected by a climate change. The interrelated and partly unknown processes involved make an analysis of the effects difficult and the results uncertain. Also the different reactions per species makes it difficult to generalize results. Some species, like several coniferous trees, show no reaction of stomatal conductance to changed CO_2 concentrations. In general, plant physiological studies show that an increase in CO_2 results in higher growth rates, lower stomatal conductance and increased water use efficiency. To simulate the water use of a forest, a realistic model of stomatal conductance (G_s) is needed. However, the exact relation between stomatal regulation, plant physiological processes and environmental variables is not fully known. This has resulted in a variety of empirical models simulating G_s.
In this study a well known empirical parameterization of G_s is applied. Given the available data and the existing uncertainties in stomatal behaviour this parameterization is believed to be adequate. However, it is expected that in the near future the stomatal regulation will be simulated more realistically.

4.2 Method

Model

A one-dimensional model is developed to simulate the water balance of a forest on an one hour time scale. The model is based on the model used by Dolman (1988) to simulate the water balance of a coniferous forest and is devided into three main submodels. Transpiration is simulated using the Penman-Monteith equation. The Gash-Rutter (Gash,1979) approach is applied to simulate the interception of rainfall. The soil water balance is simulated on a daily time scale by a simple

bucket type model. The amount of water exceeding field capacity is considered as precipitation excess and drained.
Actual stomatal conductance is calculated from solar radiation, atmospheric humidity, air temperature and soil water deficit using the regression equation according to Jarvis (1976) and Stewart (1988).

Data

Five data sets of different forests in Europe were available to calibrate the model. These have been analyzed for their potential use in this study. The data sets of the Thetford forest (1976) in England and Ede (1988/1989) in The Netherlands are used. The calibration of the coniferous forest in Thetford is described by Stewart (1988), and the calibration of the deciduous forest in Ede is derived from Hendriks et al. (1990) and Ogink-Hendriks (1994). The datasets of Ede did not include winter measurements. As water use during winter is limited due to low temperatures and low irradiation, this restriction of data is permissible to calibrate the model.
The water balance is simulated over 5 years using the KNMI-data set of 'De Bilt'. This data set covering 1974 - 1978, consists of hourly values of air temperature, air humidity, global radiation, windspeed and precipitation. The totals of precipitation of these years were 992, 635, 536, 813 and 643 mm respectively; on average 724 mm. The average over 1961- 1990 is 802 mm. The period of 5 year was relatively dry, with 1974 a wet year and 1976 a very dry one. The meteorological variables of the KNMI data set were measured above grass and are transformed to above forest conditions according to Nonhebel (1987). The forest characteristics are described by the calibrated parameters of the 'Ede' and 'Thetford' forests.

4.3 Sensitivity and climatic scenario analysis

The influence of the main model parameters on interception and transpiration were analyzed by sensitivity analysis. To integrate the results with the results of other impact research groups within the National Research Program, the scenario KNMI-2 as described in Section 2 is applied to the 'De Bilt' data. In this study this scenario is named scenario-2. The changes in temperature and precipitation are given in table 4.1. In the scenario the relative humidity is held identical to the relative humidity of the unchanged climate. Other meteorological variables are not changed. The amount of precipitation in the scenario increases strongly compared to climate scenarios described by IPCC or Kwadijk (1993). The increase in precipitation in the scenario is regarded as an increase in precipitation intensity, and not as an increase in duration.
In order to apply the scenario an estimation must be made of the forest parameters in a changed climate. In particular the leaf are index (LAI) is an important parameter. According to the review by Idso and Idso (1994), doubling CO_2 increases dry weight by 24% when water is not limiting, and by 58% when water is limiting. Trees may even be more responsive to a CO_2 increase than herbaceous plants, although most experiments are done on seedlings, leafs or small trees. According to the same authors, average increase in dry weight when nutrients are limiting, still amounts to 48%. With limited nutrients and high CO_2 the increase will be concentrated in the roots. It is unclear whether the increase in growth is sustainable. Due to the use of unacclimated plants and leaves in most experiments, and the short periods over which measurements are made, it is hazardous to transfer the results of these studies to forest (Eamus and Jarvis,

1989). For instance, the response of the assimilation rate of acclimated plants seems to be 50% lower than of unacclimated plants due to the lack of active sinks for the assimilation products (Cure and Acock, 1986).
In the scenario a modest increase of 5% in LAI and storage capacity is applied. It is expected that growth of the canopy will be limited by low nutrient availability and the maximum LAI possible considering the radiation in the canopy. The direct effect of increased CO_2 is simulated by a decrease in stomatal conductance of 30%. Based on present knowledge, these changes are regarded as realistic, though variations due to varying species composition and forest site may be large.

Table 4.1
Scenario use as input in model simulations. Change of actual temperature per hour in °C and hourly precipitation in %. Number of precipitation days is unchanged

	Winter	Spring	Summer	Autumn	Year
Temperature change	3.0	2.3	3.7	3.4	3.1
Precipitation change scenario 2	19.2	9.5	16.2	10.4	13.8

4.4 Results and conclusions

Interception
The interception of rainfall is especially sensitive to changes in evaporation rate, leaf area and related storage capacity of the canopy. Changes in temperature, air humidity and windspeed strongly affect interception. A change in air humidity of 20% results in a change in average air humidity deficit from 0.6 g/kg to 1.8 g/kg. Interception changes by about 50% for coniferous forest and by 60% for deciduous forests. An increase in storage capacity of 20% results in an increase in interception of 10% for coniferous forest and 7% for deciduous forests.
In applying the scenario, the small increase in interception for both forest types (Figure 4.1) is mainly caused by the increase in storage capacity. Relative humidity is unchanged and evaporative demand of the air is hardly increasing. Although precipitation increases strongly, it hardly affects interception because the increase is concentrated in winter, when evaporation is low. As a result both forest types show a small decrease in the ratio of interception and total precipitation.

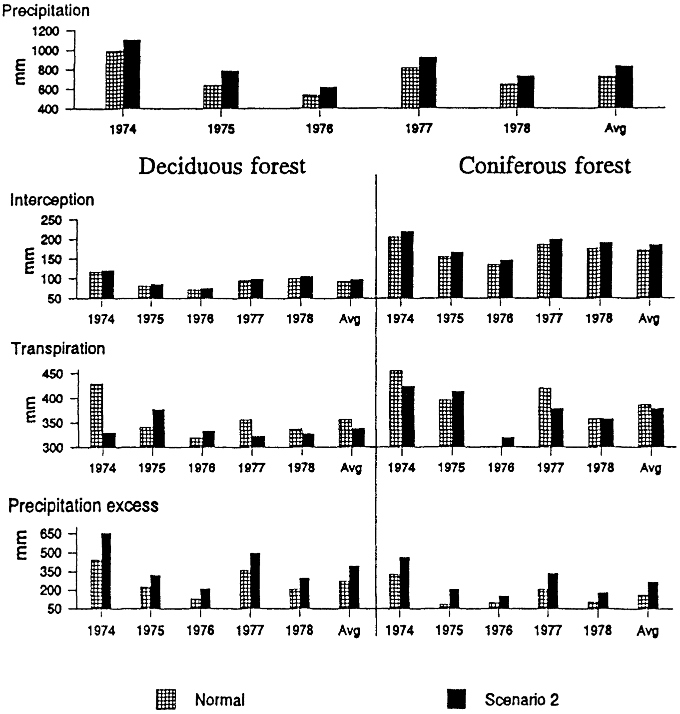

Figure 4.1
Yearly totals of precipitation, interception transpiration and excess simulated with normal climate and scenario 2

Transpiration

Using the Penman-Monteith equation, transpiration of forests is sensitive to changes in maximum stomatal conductance, temperature, air humidity and soil water availability. The sensitivity of transpiration is caused by soil water. Due to limited soil water availability, transpiration is reduced after some time. So in most years, when transpiration is enhanced during winter and spring, water shortage occurs and reduces the transpiration in summer. On the other hand, when transpiration is decreased, more water is available and transpiration during summer is not so often limited. For some years, this results in a higher total transpiration when transpiration enhancing parameters have lower values. This includes interception. When interception is increased, less water is available for transpiration.

Application of the scenario shows a small decrease in transpiration over the five year period. In dry years transpiration is limited due to low soil water content during summer. The strong increase in precipitation with a climate change leads to a higher availability of soil water, so transpiration in those years increases. But due to the lower stomatal conductance, transpiration decreases by 10-30% most of the time when water availability is not limiting (Figure 4.1).

Forest water balance

The annual water use of forest is simulated to change between -20% and +10 % depending on water availability. The average change over the 5 years is close to zero. Water use is increased when the forest stands on soil with low water availability.

The increase in precipitation results in large precipitation excesses and a reduction in the number of days with water shortage (Table 4.2 and 4.3). In winter, when the evapotranspiration of the forest is low, the large increase in precipitation will drain almost completely to the groundwater. Large discharges can be expected, especially in deciduous forests. Figure 4.2 shows a total increase in precipitation excess of 60%, with high peaks during winter.

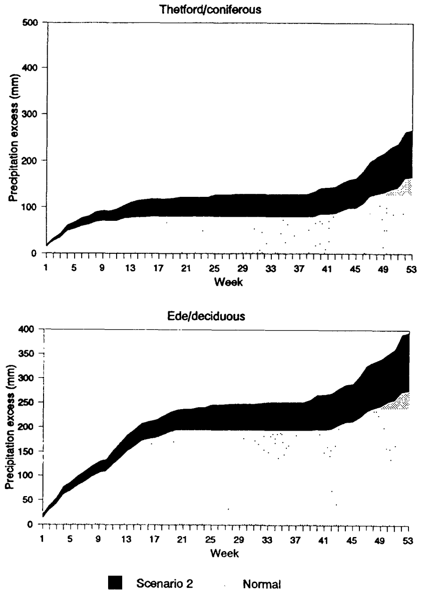

Figure 4.2
Cumulative precipitation excess per week for Thetford and Ede forests

Table 4.2
Number of days with soil water deficit above maximum for Ede deciduous forest

	1974	1975	1976	1977	1978	Avg
Normal	0	39	46	13	22	24
Scenario 2	0	18	31	0	0	9.8

Table 4.3
Number of days with soil water deficit above maximum for Thetford coniferous forest

	1974	1975	1976	1977	1978	Avg
Normal	7	42	91	15	46	40.2
Scenario 2	0	18	59	10	17	20.8

Implications
According to the simulation study winter discharge will increase strongly and summer droughts will decrease. The increase in winter discharge results from the strong increase in precipitation and not from the decrease in transpiration, which is low in winter. Compared to deciduous forests, coniferous forests diminish winter discharge.
It should be noted that the results of the study are strongly dependent on the expected increase of precipitation, the decrease in stomatal conductance, the small increase in leaf area and the assumed constant relative humidity. On the short term the stomatal conductance of most C3 species at elevated CO_2 levels decreases, but long term effects are hardly known at present. Given the uncertainties in these parameters, the limits of confidence of the present study are very wide.

The present policy to replace coniferous forest by deciduous forest to limit evaporation, will further increase drainage in a greenhouse climate. This means that frequent flooding can be expected in winter when the soil is already saturated.

Like the prediction of future climate, the prediction of the impacts of climate change on water use of forest systems is hazardous. An important reason is that data to validate the model are scarce. The response of trees to elevated CO_2 levels might mirror that of other C3-plants, but may also differ because trees are woody and perennial. Experiments with increased CO_2 concentration on fully grown forest trees are recommended to improve the confidence level of the present studies.

5. LOWLAND HYDROLOGY

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Abstract

Dynamic computer simulation models were used to carry out scenario studies, forecasting the possible effects of sea level rise and climate change on physical processes which are crucial in regional- and agro-hydrology. These effects call for water management measures on a regional scale. Attention was focused on changes in hydrology in the upper soil layers where these effects interfere with soil

water dynamics. A modified version of the two-dimensional groundwater flow model MOC of Konikow & Bredehoeft was used to simulate density-dependent deep groundwater flow and salt transport. Soil water dynamics and salt transport in the unsaturated zone were simulated with the one-dimensional model SWAP. A sea level rise of 1.2 m (worst-case scenario of IPCC, 1990), gradually imposed during a century, affects the seepage rate into polders in the studied area almost instantaneously but at a negligible rate. During the simulated period, the salinity of the seepage water remains unaffected due to the low flow velocities of the groundwater and the great path lengths to be travelled by the groundwater between the coastal area and the polders. In contrast, climate change significantly affects crop production, viz. potential and actual transpiration.

5.1 Introduction

Climate change will interfere with low-coastal hydrology int two different ways, namely sea level rise and altered meteorological conditions near the land surface. Sea level rise will probably cause increased seepage rates in low-coastal regions, leading to salinization of (shallow) ground- and surface waters. Altered meteorological conditions will affect the exchange of water and energy at the soil surface, and thus soil water dynamics in the unsaturated zone and crop production. In low-coastal regions of The Netherlands, integral water management influences the open water and the shallow groundwater systems. Agriculture, horticulture, nature conservation, domestic and industrial water supply are involved on a regional scale. As climatic change is likely to interfere with integral water supply and demand, an investigation of its possible consequences is called for. The climatic change was simulated using meteorological relationships from the KNMI (see Section 2), based upon a temperature rise of 1 °C. Simulations of the proposed temperature rise of 3 °C (IPCC, 1990) was abandoned, because of sensitivity of the available crop varieties to the changes in temperature sums. Adapting these and other physiological plant parameters to such comparatively extreme conditions was considered to be unreliable at this time. It is to be expected that varieties suited to changed conditions will be available when they become necessary. The consequences were assessed through a series of scenario studies, made with dynamic computer simulation models which were modified for this study. These studies were made in a vertical cross-section through the island of Voorne-Putten in the SW-Netherlands. This island was selected because it lies below sea level, and there is a certain amount of saline seepage there already. Also, investigations were made here earlier, providing essential data. The effect of sea level rise on saline seepage was simulated with the 2-D groundwater flow model MOC (Konikow & Bredehoeft, 1978) in cooperation with G. Oude Essink of the Technical University of Delft. Soil water dynamics and crop production were simulated using the SWAP model. SWAP is an integrated simulation tool consisting of SWACROP, a quasi 2-D model of the water (plus soluble salt) balance of a cropped soil including drainage and irrigation (Feddes et al., 1994), and WOFOST: a water-limited crop production model (van Diepen et al., 1988) made at the DLO-Centre for Agrobiological Research (CABO-DLO).

5.2 Methods

Climate scenarios

To create a climate scenario, the methods were used that are discussed in Section 2. Radiation, humidity and wind and the pattern of rainfall are assumed to remain unchanged. The increase in temperature used in the scenarios is 1 °C, resulting in a change to annual precipitation of -2% to +9%, depending on the temperature.

The meteorological files of the years 1966, 1976, 1979, 1985 and 1986, ranging from very dry to very wet, were selected as input for the changed climate. Crop production and water use were calculated for these years, first without, then with the climate scenarios. The differences in production show the effect of climate change.

Calculating crop production with SWAP

The island of Voorne-Putten, surface area 19025 ha., was divided into 761 subareas. Soil physical properties, open water levels, drainage properties, salinity and seepage rates, and land-use were collected for each subarea, 461 of which are cultivated. Production of the most frequently grown crops, potatoes, sugarbeets, winter wheat and grass, was calculated of the 461 subareas, for the five selected years, and calibrated with estimated actual harvests. Production and water use for the changed climate was then calculated by using the same years, changed by the climatic change. Higher temperatures will cause:

- maintenance respiration to increase;
- plant organs to age faster, inhibiting daily increase and harvest total of dry matter;
- temperature sums to increase faster, causing the crop to flower, mature and/or ripen (too) early.

Higher atmospheric CO_2 affects the crops (of the C3 plant type) by 4 important mechanisms (Wolf & van Diepen, 1993):

- Leaf thickness increases, meaning specific leaf area decreases,
- Light-use efficiency (crop production per unit radiation) increases,
- Maximal assimilation rate increases,
- The crop can absorb sufficient quantities of CO_2 in a shorter time, keeping the stomata open for a shorter time, and so reducing transpiration. Water use efficiency is increased this way.

The simulations were done with the same crops, but with different crop-varieties assessed to give a realistic yield under the associated climatic conditions, by changing the physiological parameters of the crop models, cf. Table 5.1 (Boons-Prins et al., 1993).

Table 5.1
Changes in plant physiological parameters to adapt to higher temperatures and raised CO_2-levels (from Wolf & van Diepen, 1993)

specific leaf	light-use area ($m^2.kg^{-1}$)	maximal efficiency ($kg.ha^{-1}.h^{-1}$ $/J.m^{-2}.s^{-1}$)	temp. sum assimilation rate ($kg.ha^{-1}.h^{-1}$)	temp.sum before flowering (°Cd)	surface until maturity (°Cd)	resistance ($s\ m^{-1}$)
Winter wheat						
1^*CO_2	18.0	0.45	40	1048	1258	40
2^*CO_2	14.4	0.55	80	1290	1171	
Potatoes						
1^*CO_2	18.0	0.45	40	150	1550	30
2^*CO_2	14.4	0.55	80	150	1800	
Grass						
1^*CO_2	25.0	0.45	40	-	-	65
2^*CO_2	20.0	0.55	80	-	-	
Sugarbeets						
1^*CO_2	18.0	0.45	40	573	1909	30
2^*CO_2	14.4	0.55	80	483	2194	

Groundwater flow modelling with MOC

After several experiments, 3-D simulation of groundwater flow was discontinued due to severe limitations of the available models. Instead, groundwater flow was simulated in a vertically oriented, 2-D cross-section through Voorne-Putten, running west to east, with dimensions 200 m (depth) by 25 km (length). The groundwater flow model used was MOC (='Method Of Characteristics'), version 3.0 of 1989, which was developed by the US Geological Survey (Konikow and Bredehoeft, 1978) as a transient solute transport model, including hydrodynamic dispersion, through the horizontal plane. In order to suit the model for application in vertically oriented cross-sections, it was adapted for density differences of groundwater (Oude Essink, 1993). In the model, the chloride concentration determines groundwater density. The number of grid cells is 100 (horizontal direction) by 20 (vertical direction); all cells are 250 m long by 10 m high. The geometry of the geohydrological system at the cross-section through Voorne-Putten is depicted in Figure 5.1. Geohydrological parameters of the subsoil, initial salinities and boundary conditions for groundwater flow were derived from Wit (1987), DGV-TNO (1984), Oude Essink (1993) and Pomper (1983). MOC requires the ratios transversal to longitudinal conductivity and dispersivity to be constant in the entire modelling domain; these were set to 0.1. Initial salinities following are shown in Figure 5.2. The following boundary conditions were imposed. The base is a no flow boundary. Along the seaside and inland boundaries where hydrostatic conditions are assumed, constant piezometric levels and salinities are maintained, determined by mean sea level, water levels in bordering channels and the density of the water. Along the upper boundary, constant phreatic levels are maintained in polder areas. These levels are determined by the water levels in open channels and collector drains. At the sand dune areas a constant rate of groundwater recharge is maintained (180 mm.yr-1).

Calibration of MOC

The geometry of the island of Voorne-Putten imposes restrictions to the modelling of groundwater flow. Simulation accuracy in a 2-D vertical cross-sectional area is hampered by the fact that important boundary conditions to groundwater flow, i.e. pressure heads at the nearby northern and southern shorelines of the island cannot be incorporated in the model. Hence, calculated seepage rates will be lower than observed ones, particularly in the central area of the domain where the effect of the inland and seaside boundary conditions of the groundwater velocity field are comparatively insignificant. It was therefore decided to concentrate model calibration in the area bordering the seaside boundary where the effect of sea level rise was to be simulated. In addition, the area used for calibration was confined to the bottom layer of the upper aquitard and the first aquifer because of the high resistance to flow of the lower aquitard (10000 d.; Pomper, personal communication). The calibration was made for seepage rates through the upper aquitard for the reference case, using the rates established by Wit (1987), by varying the kSAT of (groups of) model cells within ranges, derived from existing information (Figure 5.3). All seepage rates are averaged for specific subareas, mainly polders, with uniform open water levels.

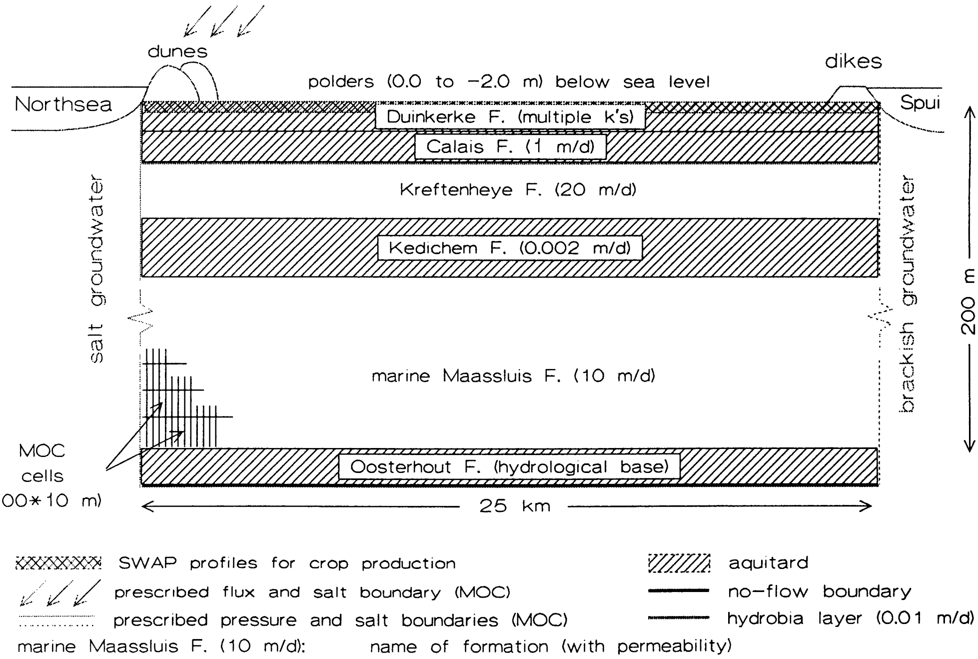

Figure 5.1
The sub-soil of Voorne-Putten partitioned into aquifers and aquitards. The hydraulic conductivities were found after calibration. Vertical scale = 100*horizontal scale

5.3 Results of simulations

Results of simulations of groundwater flow and solute transport with MOC

The effect of sea level rise on saline seepage was assessed by comparing the modelling results of two scenarios. Both simulations run for 100 years, from 1994 onward, one with a gradual sea level rise of 1.2 m, and one without sea level rise. Of these simulations, the differences in velocity and salinity of the groundwater are compared in the upper soil strata where the effect on land use is most pronounced. Figure 5.4 shows the differences in groundwater velocities between the two 100 year simulations in mg/l. Velocities below 1.10^{-4} m d^{-1} are indicated by dots. Seepage intensity does increase, but remains of minor importance in the total water balance compared to the amount of fresh water deliberately let in to flush saline surface water. It was decided not to incorporate any changes in seepage rate and groundwater salinity in the associated boundary conditions for the crop production scenario studies.

Results of Crop Production Simulation

Climatic change appears to have two opposite effects on crop production: while it tends to decrease due to higher respiration at higher temperatures, it increases due a longer growing season and to higher water-use efficiency at higher CO_2 levels. The net result is increased crop production, as shown in table 5.2.

Table 5.2

Crop production (tons (dm) ha^{-1}) for 4 crops in 5 years, with and without 1 °C climate change, calculated with SWAP. (dm = dry matter, min = minimum, max = maximum, avg = average, warmer = with warmer climate)

	Sugarbeets (t.ha^{-1} dm)			Potatoes (t.ha^{-1} dm)			Wheat (t.ha^{-1} dm)			Grass (t.ha^{-1} dm)		
year & climate	min	max	avg	min	max	avg	min	max	avg	min	max	avg
1966	11.1	15.4	13.8	11.2	14.4	14.4	5.4	7.1	7.1	1.5	11.9	10.3
warmer	11.6	20.0	15.8	11.6	20.0	15.8	7.4	9.7	9.4	4.8	15.3	13.5
1976	1.2	8.2	4.0	1.7	6.0	3.4	0.3	4.1	2.1	7.4	11.5	10.0
warmer	2.5	8.2	5.1	2.5	8.2	5.1	0.1	6.1	3.2	10.2	15.4	12.8
1979	7.7	14.6	12.4	9.7	15.0	13.0	4.7	6.9	6.8	1.0	10.8	9.8
warmer	10.4	17.4	14.7	9.7	20.8	14.7	8.1	10.4	10.1	3.8	13.3	12.0
1985	7.9	14.5	12.2	9.0	15.0	11.8	6.5	7.3	7.3	1.6	11.0	10.0
warmer	10.0	15.8	13.7	10.2	21.0	13.9	5.3	10.9	10.1	4.1	14.6	12.6
1986	7.1	14.5	9.8	4.4	12.2	6.9	2.8	7.3	6.3	3.2	11.2	10.0
warmer	9.9	15.1	12.3	4.5	14.3	7.4	2.3	10.0	7.2	7.5	15.3	13.4

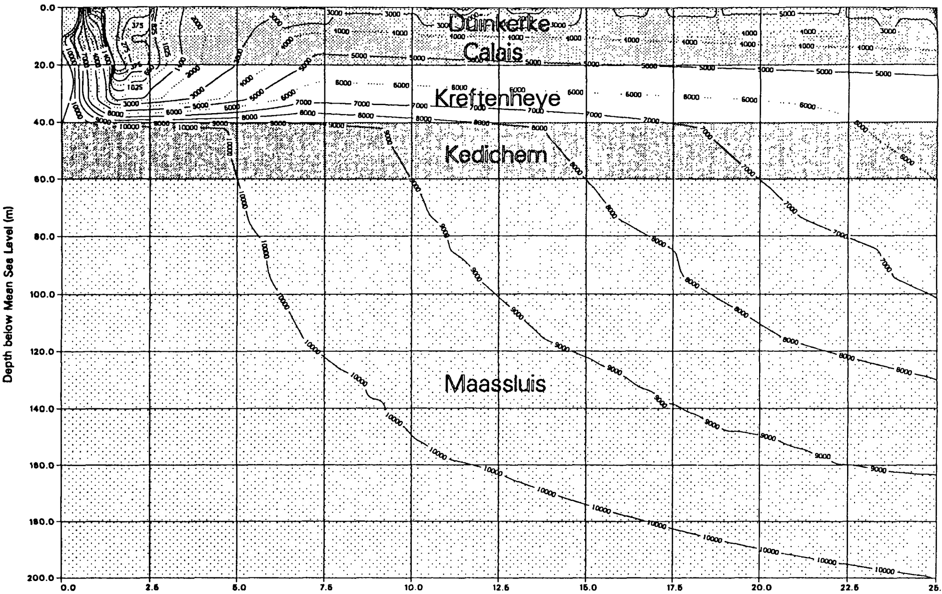

Figure 5.2
Isohalines of the groundwater (initial conditions) in the model MOC (mg/l)

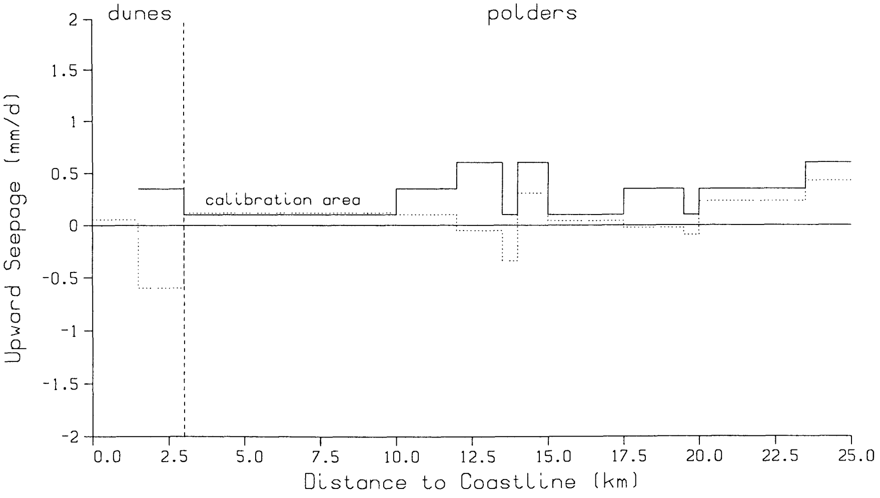

Figure 5.3
MOC-simulated seepage is compared to the seepage computed by Wit (1988) from field data. Calibration was only done for the polders close to the sea, to minimize the influence of the ignored raised open water to the north and south

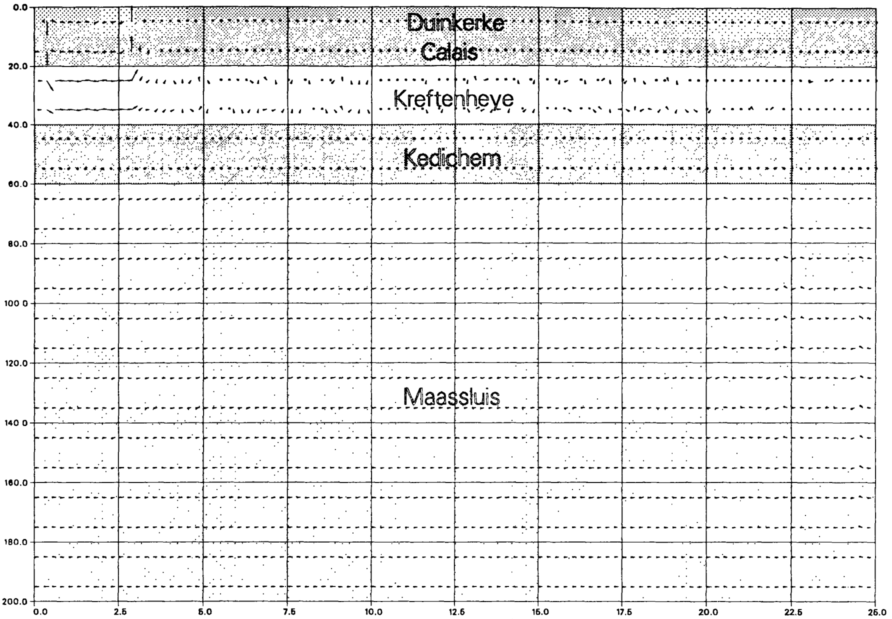

Figure 5.4
Differences in groundwater velocity-fields after simulating 100 years, with and without sea-level rise, with MOC

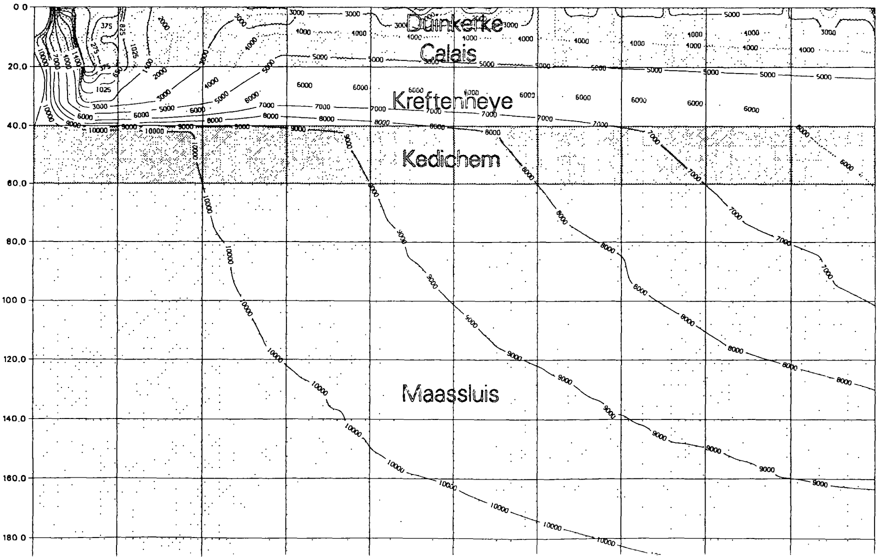

Figure 5.5
Groundwater salinity differences (%) after simulating 100 years, with and without sea-level rise, with MOC

5.4 Implications

A sea level rise of 1.2 m during the next century does not bring about a significant increase of saline seepage in the polders of Voorne-Putten. Instead, human intervention, i.e. maintaining deep phreatic levels in these polders, and the associated land subsidence, are decisive in this respect. A temperature increase of 1°C and increased precipitation are favourable conditions for increased crop production rates, probably with only an occasional need of additional fresh water supply.

If the increase of average temperature is greater than the assumed 1°C, it is likely that additional fresh water will be needed to balance increased evapotranspiration. Possibly the climate induced changes in the discharge regimes of the rivers Rhine and Meus will make it necessary to increase fresh water storage capacity. See also Section 6. Effects of changes of land use on agricultural water demands have been studied in Section 3.

6. RIVER DISCHARGE

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Abstract

Climate change influences the water balance of drainage basins in several ways. In a project of the International Commission for the Hydrology of the Rhine basin the possible consequences for the discharge regime of the Rhine are investigated. In the first phase of this project detailed models have been developed and applied for selected sub-basins and a rough water balance model has been developed for the whole Rhine basin. In this study results are presented for climate scenarios assuming an increase in temperature of about 3°C and an increase in annual precipitation. The consequences of such a climate change are largest in the Alpine part of the Rhine basin, but are also considerable for the basin as a whole. In general the Rhine changes towards a rain-fed river. The winter discharge increases, which can have consequences for safety, and summer discharge decreases with consequences for shipping, industry, agriculture and nature.

6.1 Introduction

Climate change influences the components of the water balance of drainage basins in several ways. Precipitation patterns may change and because of a higher temperature also the accumulation and melt pattern of snow. Evapotranspiration is directly influenced by an increase in temperature. In this respect also adaptions of the physiological behaviour of plants to an increased CO_2-concentration are important. Changes in these water balance components will of course affect the discharge. Furthermore climate change may induce changes in land use, which is an important factor in evapotranspiration and runoff processes.

The river Rhine is economically the most important river of Western-Europe. Its drainage basin, see figure 6.1, covers from the source in Switzerland to the mouth in the North sea, an area of 185.000 km^2 and is habitat to over 50 million people. The river is one of the most intensively navigated inland waterways in the world and is of major importance for the supply of water to large socio-economically important areas. Changes in the discharge regime can have consequences for safety and for the water availability for shipping, industry, domestic use, agriculture, the natural environment and recreational purposes. If possible changes are known, counter measures can be formulated to minimize negative effects.

Against this background, the International Commission for the Hydrology of the Rhine basin (CHR) initiated in 1989 a project to assess the consequences of climate and land use changes for the discharge regime of the river Rhine. Since a proper tool for this was lacking, the main purpose of the project was to develop a water management model for the whole Rhine basin. This model should be suitable to analyze the changes of total discharge and its distribution over the year as well as changes in height and frequency of discharge peaks. At the same time it should also be used to examine the effectiveness of counter measures. Several institutes from the Rhine riparian states cooperate in the project (Parmet, 1993a). The Netherlands contribution is incorporated in the NRP.

6.2 Method

The water management model for the Rhine basin has to meet several requirements. To have a certain guarantee it is also valid under the changed conditions it will be used for, the model must have a physical basis. This is especially true for those processes that are directly influenced by changes in climate and land use. This implies that the spatial variability within a basin must be taken into account. To be able to simulate peak flows, a minimum temporal resolution of one day is required. In mountainous areas this has to be even smaller. In view of the complexity of the area and consequently of the model, it has been decided to phase the project. In the first phase different models for representative drainage basins of characteristic parts of the Rhine basin must be developed. The Rhine basin has therefore been divided in three more or less distinct areas, the "alpine", the "middle mountains" and the "lowland" area. The relevant hydrological processes differ within these areas, for example snowmelt in mountainous areas versus groundwater flow in the lowland. To give in short term preliminary estimations on the effects of climate change, in the first phase also a rough model for the whole Rhine basin must be developed. In a second phase the models it is planned to improve, extend and combine the models.

Since reliable information on climate change is not yet available, climate scenarios have to be used (see Section 2). Developments in land use are, if possible, even more uncertain than changes in climate. Hence also for this parameter scenarios have to be used, which are described in Section 3.

The first phase of the CHR project is almost finalized. Several hydrological models have and are being developed but also existing models have been applied for relatively small representative basins. For the alpine area an existing hydrological model, the IRMB model, was applied for several small drainage basins (Bultot,

1992, Schädler 1992). This model computes the evapotranspiration, snow cover and melt and discharge on a daily basis. Because of the temporal resolution, it is not suited to simulate peak flows in mountainous areas. Therefore a water management model is being developed with a time step of one hour, based on a hydrological forecasting model for the Swiss part of the Rhine basin.
In the middle mountains area, a hydrological model is being developed for Sauer basin, a sub-basin of the Mosel. This model has a very detailed spatial resolution and can operate on hourly and daily basis. The model is not yet operational. For another sub-basin, the Saar, in the near future an existing model will be applied.
The lowland model is being developed for the drainage basin of the Overijsselsche Vecht (Parmet, 1993b). The hydrological component of the model is used to compute the daily evapotranspiration and discharge for sub-basins. It consists of a groundwater model, an unsaturated zone model and a rainfall-runoff model. The flow-routing component of the model combines the sub-basins and routes their discharges towards the mouth of the Overijsselsche Vecht.

For the Rhine basin as a whole the waterbalance model RHINEFLOW was developed (Kwadijk, 1993). This model is designed to study the sensitivity of the discharge of the Rhine and its main tributaries for a climate change. It is a simple water balance model based on a Geographical Information System. Computations of evapotranspiration, snow melt and discharge are carried out for grid cells of 3*3 km on a monthly basis.

6.3 Results

Effects of climate change, representative basins; Alpine area
With the IRMB model the effects of a climate change for several components of the water balance were simulated for three drainage basins, Murg, Ergolz and Broye. A climate scenario as defined by Bultot was applied (Bultot, 1988). The monthly temperature and precipitation changes are given in table 6.1. The average temperature increases with 2.8°C and the annual precipitation with 54 mm (5%). Also changes in net terrestrial and global solar radiation and cloudiness are assumed. Changes in physiological behaviour of plants were not taken into account. Computations were carried out for the period 1981 to 1988.

Table 6.1
Monthly temperature (T) and precipitation (P) according to the Bultot scenario, used for representative alpine basins and a scenario based on the method developed by the KNMI, used for the representative lowland basin

Month	J	F	M	A	M	J	J	A	S	O	N	D
T_{Bultot}, °C	3.1	3.4	3.4	3.1	2.8	2.7	2.5	2.3	2.3	2.7	2.8	3.2
P_{Bultot}, % 1)	10	14	11	10	-1	-2	-2	-2	0	6	10	10
T_{NRP}, °C	3.0	3.0	2.3	2.3	2.3	3.7	3.7	3.7	3.4	3.4	3.4	3.0
P_{NRP}, %	21	20	15	13	5	12	11	9	3	8	19	18

1) The percentual change is an average for the three basins Murg, Ergolz and Broye

According to the computations annual potential evapotranspiration increases with about 10%. Actual evapotranspiration increases somewhat less because during the summer period there is a slight decrease in soil moisture. Discharge increases during the winter period with about 10%. This is due to the fact that the amount of precipitation increases and less precipitation is stored as snow. Furthermore the accumulated snow melts faster. The duration of the snow cover decreases considerably, especially below an altitude of 1500 m. Discharge in spring decreases slightly with 1%, and in summer discharge decreases with about 15%. This follows from less snowmelt, a larger evapotranspiration and a slight decrease in precipitation. The total annual discharge hardly changes. The daily maximum discharge increases and the daily minimum discharge decreases.

Effects of climate change, representative basins; lowland area

For the lowland area, climate scenarios were generated with the method developed by the KNMI within the NRP (see Section 2). In the same way as for the study to the water balance of forest (Section 4), a precipitation scenario was constructed based on the KNMI-2 method, with a temperature increase of about 3°C, and unchanged air pressure. This resulted in an increase in annual precipitation of 13%. The monthly changes in precipitation and temperature are given in table 6.1. Compared to the other scenarios used in this study, this scenario is rather wet. Computations were carried out for a sub-basin of the Overijsselsche vecht basin, the Radewijkerbeek, for the period 1965-1990. On the one hand to stay in line with the results of other CHR-studies presented here, and on the other hand to illustrate its possible effects, computations have been carried out without and with taking into account changes in plant physiological characteristics.

Without considering adaptions of plant physiological properties, referred to as scenario 1, the increase in temperature results in an increase of the actual evapotranspiration with 11% (55 mm). The annual increase in precipitation of 13% (102 mm) exceeds the increase in evapotranspiration, hence the precipitation excess increases. Consequently the annual discharge increases. From 6. 1 it can be seen that this increase is 16% (scenario 1). The winter discharge increases with 21% and the summer discharge increases too, with 9%. Although the effect of the increase in evapotranspiration is largest during summer, it does not exceed the increase in precipitation. As in the alpine areas the annual amplitude of the discharge regime increases. With this wet climate scenario no increase of problems with water shortages is expected. However the maximum discharge for the period 1965-1990 increases considerably with 29%. With this scenario problems with water surpluses could therefore be expected. As an example the daily discharge is given in figure 6.2 for present and for scenario 1 for the year 1981. The figure clearly shows the increase in the peak flow in March.

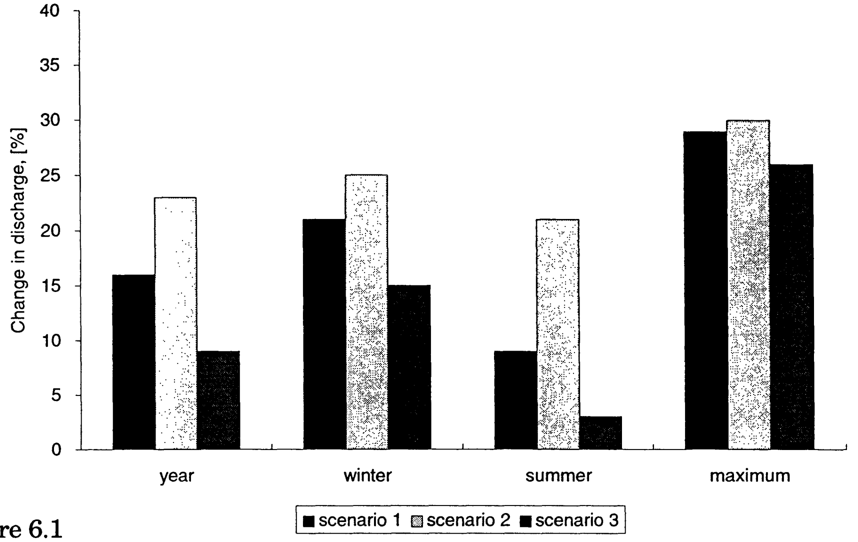

Figure 6.1
Changes in discharge characteristics for the Radewijkerbeek, for computations with changed climate, NRP scenario (scenario 1), with changed climate and adapted plant physiology (scenario 2) and with changed climate and changed land use (scenario 3), for the period 1965-1990

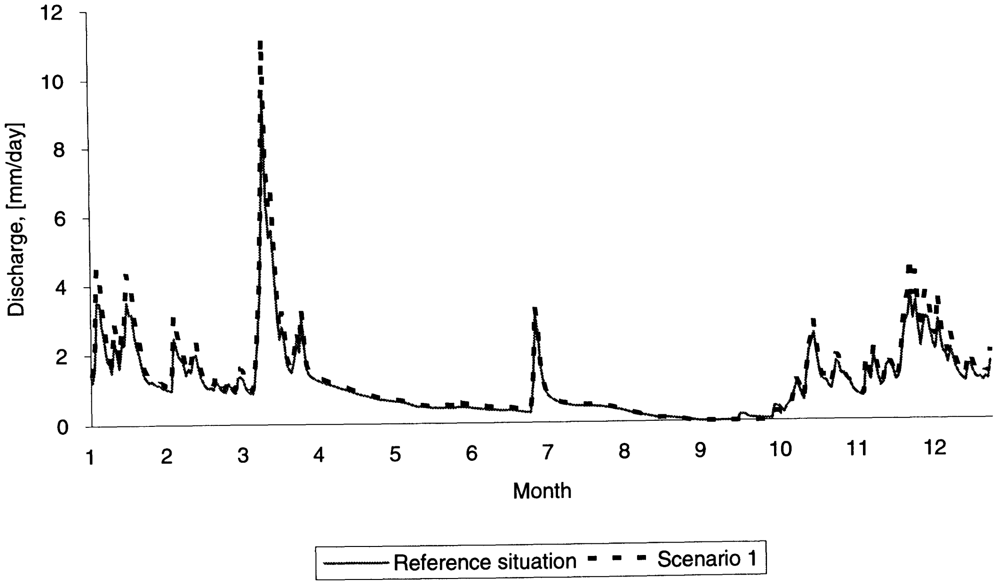

Figure 6.2
Daily discharge of the Radewijkerbeek for the reference situation and for computations with changed climate, NRP scenario (scenario 1), for 1981

An increased CO_2-concentration influences plant physiology. For most plants the water use efficiency increases and the biomass production increases . An increase in temperature for the temperate zones generally leads to an increase in production too (see also Sections 3, 4 and 5). Whether the increase in production exceeds the increase in water use efficiency and consequently how evapotranspiration changes, is not yet clear. Present knowledge indicates, for doubled CO_2-concentrations and an increase in temperature of about 1.5° C, a small decrease in evapotranspiration for most crops and forests (Roetter en van Diepen, 1994; Hendriks, 1994). For forests, even with a temperature increase of 3°C evapotranspiration may decrease, as shown in Section 4. Based on this knowledge, plant physiological parameters were provisionally adapted in the lowland model. Computations with the same climate scenario as used for scenario 1 (see table 6.1), but with adapted plant physiological characteristics, were carried out for the period 1965-1990. These computations are referred to as scenario 2. The actual evapotranspiration increased with 7%. This increase is 4% less than for scenario 1, which can be explained from the increased water use efficiency of crops. Consequently the increase of the net precipitation excess is larger. The annual discharge increases therefore more, instead of 16, with 23%. The differences between scenario 1 and 2 with respect to the winter discharge are relatively small, as can be seen from figure 6.1. During this season evapotranspiration plays a minor role (see also Section 4). The increase of 25% is somewhat larger. The effects of a smaller increase in evapotranspiration strongly affect the summer discharge. Compared to scenario 1 this increases considerably more, 21% instead of 9%. The influence on the maximum discharge is small, since in such situations evapotranspiration plays a minor role.

Effects of climate change, Rhine basin

Consequences for the whole Rhine basin have been computed with the RHINEFLOW model. The sensitivity of the discharge regime was examined with a wide range of climate scenarios for the period 1956 to 1980 (Kwadijk, 1993). Here the results of computations with one scenario, the socalled BAU-best scenario, are presented. As already indicated in Section 2, this scenario in general agrees with the scenarios used for the representative basins in the alpine and lowland area. It assumes an average rise in temperature of 3.5°C and a small change in precipitation in summer and an increase of winter precipitation (see table 6.2). Changes in the physiological characteristics of plants were not taken into account.

Table 6.2
BAU-BEST scenario for temperature (T) and precipitation (P), for different areas in the Rhine basin (Kwadijk, 1993)

Part of Rhine basin	Year		Summer		Winter	
	T,°C	P, %	T,°C	P, %	T,°C	P, %
North	3.5	11	2.9	4	4.3	19
Middle	3.5	8	2.9	-1	4.2	19
South	3.5	7	2.9	-4	4.1	19

For the alpine part of the Rhine basin, the changes as computed with RHINFLOW have the same direction as the results for the representative alpine basins. As can be seen from figure 6.3, the discharge during winter increases. This is caused by increased precipitation and snow melt. During summer the discharge decreases due to a smaller contribution of melt water, increased evapotranspiration and a slight decrease in precipitation. The increase in winter discharge is much larger than for the representative basins, up to 100% with an average of 60%. This can be explained partly from the used scenarios. Both the increase in temperature and in precipitation is smaller for the Bultot scenario compared with the BAU-best scenario. Furthermore it can be explained by differences in model components, especially the snow component, and off course the considered area is not the same. The changes during summer are comparable, both for the alpine area as a whole and for the representative basins in the alpine area, a decrease of about 15% was computed.

The changes for the area downstream, the middle and lowland part, are much less pronounced. The discharge increases during winter and spring and decreases during summer and autumn, as can be derived from figure 6.3. The increase in evapotranspiration causes the soil water deficit to increase. As a result, summer discharge decreases, but because part of the winter surplus is stored as groundwater, not until July. The water surplus during autumn is partly used to replenish soil water, which explains the decrease of discharge during autumn. Because the scenario used for the representative basin for the lowland is wetter, especially for the summer period, than the BAU-best scenario, the changes in discharge are not directly comparable.

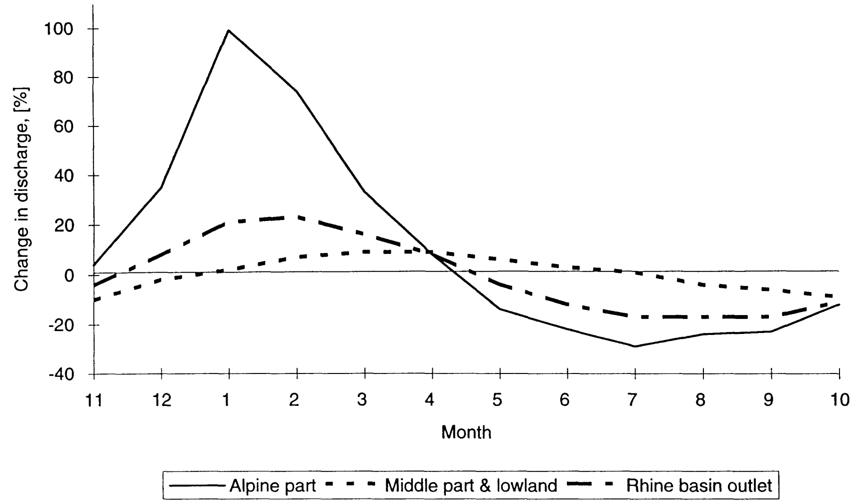

Figure 6.3
Changes in monthly discharge for the alpine part, the middle and lowland part and the outlet of the Rhine Basin, for computations with the BAU-best scenario, for the period 1956-1980

Where the Rhine enters The Netherlands, near the basin outlet, the changes in the alpine, middle and lowland part are combined. The annual changes are small, the discharge increases with 2%. However, winter and spring discharge increase with about 15%, and summer and autumn discharge decrease with about 10%. Due to the changes in the alpine area the character of the river Rhine changes from a combined rain-fed/snow-fed into a rain-fed river. The discharge pattern will become less smooth and the difference between maximum and minimum flows will increase. The number of months with low flows will increase. For example the number of months with an average discharge below 1000 m^3/s increases for the period 1956 to 1980 with 13, which is about 60%. To make an assessment about peak flows with the monthly discharges computed by RHINEFLOW, a relation between average monthly flows and peak flows was derived (Kwadijk en Middelkoop,1994). This relation can be applied with a sufficiently small reliability interval for discharge peaks up to 7000 m3/s. Therefore the relation can be applied for the study to sedimentation processes in the river and floodplains (see Section 8). The considered period is however too short to give fundated results for the design discharge, and hence about consequences for safety. However, model results indicate that the critical discharge (recurrence time of 1250 years) related to the safety standard of the river dikes may increase, with a maximum of 1500 m^3/sec (Kwadijk en Middelkoop, 1994).

Effects of land use change

The effects of changes in land use on discharge characteristics have been studied only very roughly. A first assessment showed that for the entire Rhine basin the impact of land use changes on the river Rhine discharge were smaller than climate changes according to the Business as Usual scenario (Kwadijk,1993). The land use schematization of the model RHINEFLOW is very coarse, and in its present form it is not very suitable to study the effects of land use changes. Furthermore the land use scenarios for the Rhine basin as described in Section 3, were developed only very recently. Computations have therefore just been carried for the lowland area, for the sub-basin of the Radewijkerbeek. A land use scenario was generated based on the "Minus" projection for the region Netherlands- East. In this scenario in total 35% of the agricultural land is vacated. This is divided over potatoes (-75%), sugar beets (-60%), cereals (-35%), maize (-50%) and grass (-30%). In total 10% of the agricultural area is changed into nature, the remaining 25% into forest, equally divided over coniferous and deciduous forest. The urban area, which is very small in the Radewijkerbeek sub-basin remains constant. Computations with this land use scenario were carried out for the period 1965-1990. Climate conditions were adapted according to the KNMI-2 scenario. Plant physiological characteristics were not adapted.

The computation results, referred to as scenario 3, show an increase in evapotranspiration of 15%. Compared to scenario 1 this is 4% larger, which is mainly caused by the increase of the area coniferous forest. In Figure 6.2 the changes in discharge characteristics are given for scenario 3. Not surprisingly the increase in annual discharge is smaller than in scenario 1. The increase is 9% compared to 16% for scenario 1. The effect of the increased evapotranspiration is of course largest during summer. Although the increase in precipitation still exceeds the increase in evapotranspiration, the increase in summer discharge is only 3% for scenario 3, compared to 9% for scenario 1. The effect of the increased area of coniferous forest is also visible during winter. The total amount of interception of precipitation increases, and therefore the increase in discharge for scenario 3 is smaller than for scenario 1, 15 respectively 21%. For the flat lowland area changes in land use mainly influence evapotranspiration. Since the extreme discharges are mainly determined by precipitation, the increase in maximum discharge for scenario 3 is comparable with scenario 1. The effects of the land use scenario are smaller than those resulting from the climate scenario, but are still considerable, especially for total discharges.

6.4 Implications

Interim results of the CHR project show that climate change can have considerable effects for the discharge regime of the Rhine. With the assumed scenario for the Rhine basin, the winter discharge increases considerably. This could have consequences for safety, but the models are not yet suitable to assess consequences for maximum peakflows. The contribution of water originating from snow melt from the Alps during the summer period decreases, which is an important reason for a decrease in summer discharge. Furthermore evapotranspiration is expected to increase, which contributes also to a decrease in summer discharge. Consequently the frequency of periods with low flows increases. It should be noted that in the RHINEFLOW study the effects of increased CO_2 on water use have not yet been taken into account. This would probably result in a reduced increase in evapotranspiration of agricultural crops and for forests even in a decrease as concluded by Lankreijer (1994). However this is not expected to have a large influence on the conclusions with respect to low flows, since the water originating from snow melt is dominant in such periods and Lankreijer (1994) shows that for dry years even for forests evapotranspiration increases. For water management in The Netherlands an increased frequency of low flows implies increasing costs for shipping. Ships can be loaded less and have to wait longer for sluices and bridges. Costs of electricity production will increase too. To avoid environmental problems with the temperature of cooling water, other more expensive, production units have to be brought into operation. More frequent intrusion of salt water can cause problems for intake of water of certain polders. This may cause damage to agriculture. In general the changed discharge regime will also influence river morphology (see Section 8).

The effects of land use changes have not yet been studied in detail. From first computations it can be concluded that for lowland areas the total discharge rather than peak discharges will be affected. For the alpine and middle mountains area it is expected that also the peak flows are influenced. Further study is required.

The model RHINEFLOW in its present form is a useful tool for sensitivity analysis. However, the simple process descriptions and the poor quality of the underlying database, limit its applicability. On the other hand the detailed models are only available for a relatively small part of the Rhine basin. To extend these models for the whole basin is a time consuming task. Therefore a promising direction is to couple the rough and the detailed models, for example with transfer functions. RHINEFLOW has to be refined in time and space for this. Furthermore the detailed models have to be applied also in other characteristic areas, to cover the variability within the Rhine basin in a better way. It is recommended to investigate the possible effects of climate change also for other important river systems, like the Meuse. A similar approach as in the CHR project can be applied.

The largest uncertainty in climate change impact studies has to do with the climate scenarios. For decision makers the uncertainty interval of possible impacts should be as small as possible. It is therefore very important that the development of consistent and plausible climate scenarios continues.

7. EROSION
Catchment basin

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Abstract

Major source areas of the suspended sediment load of the river Rhine have been identified and the relationship between soil structure stability and climate in selected sediment source areas has been studied. The location of the main sediment source areas has been assessed with a mass balance method. Important source areas appeared to be the Aare basin and the Neckar basin. The influence of temperature on soil erodibility was investigated by comparing relevant properties of the same loess derived soil types under different meso-climatological and land

use conditions. No correlation of soil structural stability with climate could be established.

7.1 Introduction

Each year on average 3.1 million tons of suspended sediment enter The Netherlands via the Rhine. About two thirds of this sediment is deposited in The Netherlands. The other one-third reaches the North Sea, part of which moves along the Dutch coast to the Wadden Sea. This suspended sediment has important consequences for management and policy development which relate to:

- the sediment budget of the lower courses of the Rhine, including the embanked floodplains ('uiterwaarden'),
- the sediment budget of the Delta waters, the Dutch part of the North Sea and the Wadden Sea,
- the scale of mud dredging works in the Rhine, including the Rotterdam harbours,
- problems of water quality and pollution caused by chemicals (heavy metals, toxic organic compounds, nutrients) adsorbed to suspended sediment particles and present in recent mud deposits.

The suspended sediment load of the Rhine derives from erosion of the beds and banks of the river and its tributaries, but mostly from the valley side slopes and the sloping interfluve areas between the numerous first and second order branches of the Rhine system. The sediment from the valley side slopes and the interfluve areas is transferred to the river channels by a set of processes, collectively referred to as the 'slope forming processes'. These include processes of slope wash under natural vegetation and processes of accelerated soil erosion (sheet and rill erosion) on agricultural land.

The occurrence and rate of soil erosion is controlled by a number of factors, viz. ability of rainfall to cause erosion (erosivity), resistance of the soil to erosion (erodibility), length and steepness of slopes and land use. Climate change may, directly or indirectly, affect all of these factors. For this study the impact of climate change on soil erodibility was selected, because this is an under-developed research area. Soil erodibility is primarily controlled by soil structural stability. Climate affects soil structure through its influence on the organic matter status of the soil, which depends on biomass production and soil (micro)biological activity. Soil structure is characterized by the presence of soil aggregates, clusters of soil particles which mutually adhere by chemical and physical binding forces. In surface soils, these forces are mainly controlled by organic matter. Macro-aggregates (>250 μm) are mainly stabilized by plant roots and larger fungi. Micro-aggregates (20-250 μm) are bound together by decomposed organic substances. Micro-aggregation in the size class 2-22 μm is mainly caused by clay particles, and to a lesser extent by organic materials. The rate of structure development and structure breakdown is dependent on the dynamics of soil organic matter, which, in turn, is controlled by soil moisture and soil temperature regime. The impact of climate change on soil erosion will be largest where soils are most susceptible to erosion. A class of soils that are highly sensitive to erosion, are loess soils, which are wide-spread in the Rhine basin.

Objectives of research were: (a) to identify the main source areas of the suspended sediment load of the Rhine under present-day climatic conditions, and (b) to analyze the influence of temperature on soil erodibility in selected source areas of suspended sediment. The approach was a comparative study of soil erodibility in different parts of the Rhine basin with different temperature conditions under the current climate. Existing differences in erodibility between areas with different temperature regimes are an indication of the change in soil erodibility that will possibly occur as a consequence of climate change.

Starting date of the research project was 1st January 1993. Duration is two years. In this report results of the first year of study are summarized.

On the global level the research project is related to three IGBP core projects which deal with the hydrological and geomorphological study of soil erosion and river basin dynamics:

- Land-Ocean Interactions in the Coastal Zone (activity: catchment basin dynamics and delivery),
- Biospheric Aspects of the Hydrological Cycle (activity: biospheric control of waterborne transport, and integrating waterborne transport at the river-basin scale),
- Past Global Changes (effects of climate and human impacts on the biosphere).

On the national level there is a strong relationship with the research projects carried out at the State University of Utrecht and Rijkswaterstaat/RIZA. This concerns the study of the water balance and water discharge of the Rhine basin, the movement of sediment in the Rhine, the sedimentation rate of suspended solids on the embanked floodplain of the Rhine and Meuse, and their sensitivity to climate change (Asselman and Middelkoop; Parmet et al., this volume).

7.2 Methods

Location of suspended sediment sources

The suspended sediment that enters The Netherlands at Lobith originates from the part of the Rhine basin between the Bodensee and Lobith (see figure 7.1). This part of the Rhine basin has a surface area of roughly 159,000 km2 which shows a wide range of climatic, geologic, geomorphologic and pedologic conditions. The river itself is regulated by man. Sediment is trapped by weirs and in natural and man-made lakes. In some cases sediment is removed from the river system by dredging. It was outside the scope of the project to locate the origin of the suspended sediment with the aid of tracing or finger-printing techniques involving mineralogical or chemical analyses. Instead, a mass balance approach was followed. The basis of such an approach is given by long-term measurements of daily water discharge and suspended sediment concentration at a number of stations along the Rhine and its main tributaries. The differences in sediment load between measurement points are due to contributions from sediment sources between measurement points or to losses due to sedimentation (and dredging) between points. This method does not differentiate between natural and human sources of sediment. Therefore, additional data of the suspended sediment output of the waste waters of the French Potassium Mining (MdPA) were used to complete the balance.

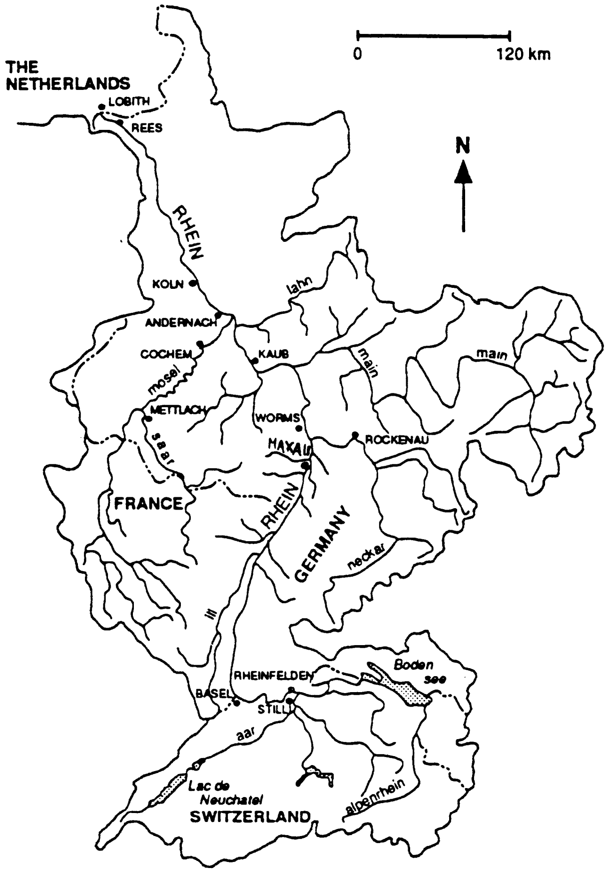

Figure 7.1
The Rhine basin upstream of Lobith (The Netherlands). Figure adapted from Kwadijk and Middelkoop (1994)

Identification of climate effects on soil structure stability

The effect of climate on soil structure was studied on a meso-scale by comparing loess soils on north and south-facing slopes and on a macro scale by comparing loess soils from a part of the Rhine basin with a more continental climate (Kraichgau) to a part with a more maritime climate (Nordrhein-Westfalen), while keeping other environmental factors, such as geology and topography, constant. Besides climatologically induced variations, also differences in soil structure between land use types (arable land and forest) and between topsoil and subsoil were investigated (see figure 7.2).

Soil samples were tested on presence of lime, organic carbon content, aggregate stability (drop test), soil texture and micro-aggregation (Microscan). With statistical methods of data analysis (cluster analysis, Analysis of Variance, Mann-Whitney U-test) differences between groups of samples were evaluated (Van der Drift, 1994).

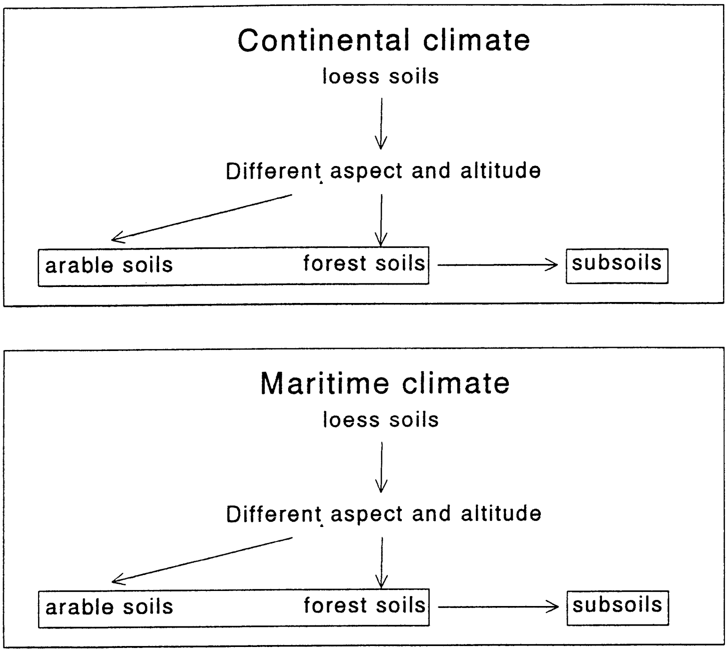

Figure 7.2
Schematic representation of field sampling strategy

7.3 Results and conclusions

Sediment sources

The major sources of suspended sediment in the Rhine have been identified from the share of the sediment amount at Lobith in table 7.1. Rate of erosion (ton/ha/year) is calculated by dividing this share by the area of the river basin. This is an indication of the severity of erosion in the catchment. The sediment loads of the sources upstream of Iffezheim (km.334) are reduced with 40% for sediment retention upstream of the dams in the Rhine. Of the human sediment sources, the industrial waste-waters from the French potassium mining and German soda industries contribute to nearly 0.5 Mton suspended sediment/year at Lobith, or 15% (corrected for sedimentation).

The natural sediment sources in the Rhine basin are characterized by a yearly cycle: in summer the Aare is the main contributing river; in winter and spring the Neckar, Main and Mosel have a strong influence. If we look at the annual totals of table 7.1, the Swiss Aare system is an important source of suspended sediment, with a corrected mean annual contribution of 0.55 Mton/year, which is equal to an average soil loss of 0.3 ton/ha/year. The Main has the second-highest sediment contribution (0.5 Mton/year), but a slightly lower erosion figure than the Neckar, which delivers a mean annual sediment output of 0.45 Mton, or 15% of the load at Lobith. This means a soil loss of 0.3 ton/ha/year. No data were available for a separate calculation of the contribution of the Mosel and the Lahn.

Table 7.1
Major sources of suspended sediment in the Rhine

Source	Sediment load Mt/y	Amount at Lobith* Mt/y	erosion+ %	ton/ha/year
Bodensee	0	0	0	0
Thur	0.2	0.12	3.9	0.7
Aare,Reuss,Limmat	0.91	0.55	18	0.3
Trib. Basel-Maxau	0.16	0.096	3.1	•
Neckar	0.45	0.45	15	0.3
Main	0.50	0.50	16	0.2
Mosel and Lahn	0.70	0.70	23	0.2
Trib. Maxau-Rees	0.17	0.17	5.5	•
MdPA	0.65	0.39	13	n.a.
Other industries	0.09	0.09	2.9	n.a.
Households	0.02	0.02	0.65	n.a.
Algae	0.01	0.01	0.32	n.a.
Total	4.32	3.1	100	

*: corrected for sedimentation upstream of dams (40%)
•: unknown
+: calculated from 'amount at Lobith'
n.a.: does not apply
Data were received from the Bundesanstalt für Gewässerkunde, Koblenz, Germany

Soil structural stability and soil erodibility

Summaries of aggregate stability analyses with the drop test method are given in tables 7.2 - 7.5. No statistically significant difference in aggregate stability was found between two climatologically different parts of the Rhine basin (Van der Drift, 1994), although the data suggest that soils in an area with a more continental climate have more stable aggregates than soils under a more maritime climate. The tests give an indication of the present state of soil structure. This does not exclude a difference between the development of aggregate.

Table 7.2
Summary of drop-test data for Kraichgau and NRW topsoil samples, May-June 1993. Statistics are listed for all samples, and arable land only

Region	Kraichgau	arable	NRW	arable
Average AS	1.08	1.27	1.55	1.75
St. dev. AS	0.873	0.557	1.02	0.961
St. skewness AS	3.39	- 0.0867	0.630	-0.135
Number of samples	25	15	14	4

Table 7.3
Summary of drop-test data for topsoil samples from arable and forest soils, May-June 1993

Land use	Arable	Forest
Average AS	1.46	0.850
St. dev. AS	0.874	0.943
St. skewness AS	2.65	2.64
Number of samples	25	14

Table 7.4
Summary of drop-test data for topsoil and subsoil samples, May-June 1993

Soil horizon	Topsoil	T-arable	Subsoil	S-arable
Average AS	1.011	1.37	2.49	2.65
St. dev. AS	0.690	0.661	1.22	1.58
St. skewness AS	1.68	0.657	-0.405	-0.607
Number of samples	34	19	6	3

Table 7.5
Summary of drop-test data for topsoil samples from North- and South-facing slopes, May-June 1993

Aspect	South	S-arable	North	N-arable
Average AS	0.771	1.16	1.05	1.47
St. dev. AS	0.543	0.593	0.556	0.725
St. skewness AS	0.612	-0.142	0.942	1.07
Number of samples	12	9	12	8

AS = index of aggregate stability; NRW = Nordrhein-Westfalen
(Source of tables 7.2 - 7.5: Van der Drift, 1994)

Stability, due to differences in climate

On a micro scale, aggregates are slightly more stable on south- and southwest-facing slopes (warm, dry) compared with northerly- and northeasterly exposed slopes (cold, moist). However, this difference was not large enough to become statistically significant. If soils with different land use are compared, the conclusion drawn from the Mann-Whitney test (Van der Drift, 1994) is that aggregate stability is highly influenced by differences in land use. Soils with agricultural land use have a less stable structure than forest soils. Forests are different from arable fields: they have a more shady, constant, temperate and moist climate, which results in more organic matter, with a different composition. Not only the amounts of organic matter, but also the composition and dynamics of organic materials, including soil biologic activity are important controlling factors of soil structure. This is in agreement with the fact that the topsoils have a more stable structure than subsoils. The soil processes which are responsible for soil structure formation and stabilization, are strongly dependent on fluctuations and range of soil temperature and soil moisture.

Implications and recommendations

From the results of the first year of study it can be concluded, that a temperature change of 3°C in the Rhine basin probably will have no profound effect on soil structural stability and soil erodibility.

This does no exclude an impact of climate change on soil erosion and sediment production in the Rhine basin. Sediment production on agricultural land will increase in summer due to higher rainfall intensities which strongly control the rate of soil erosion (Kwaad, 1991). For instance, a 40% increase of mean hourly rainfall intensity will occur, when mean day temperature rises from 20 to 23°C. (Klein Tank and Können, 1993). Runoff and soil loss from agricultural land will increase in winter due to an increased probability of occurrence of saturation overland flow (Kwaad, 1991), caused by a 19-20% increase of winter rainfall (Können, this volume).

Land use changes, such as foreseen for the decade 2040-2050 by Parmet (this volume), viz. a 20-24% decrease in area of agricultural land, will lead to a decrease of sediment production in the Rhine basin, if this 20-24% surface area is forested and if the reduction of the area of crop land is not counteracted by an increased rate of soil loss per ha of remaining crop land.

Increased winter discharge volumes and increased daily maximum discharges of the Rhine, such as mentioned by Parmet et al. (this volume), may lead to accelerated remobilization of sediment stored as alluvium along the Rhine and its tributaries, e.g. the so called 'Auelehm'. On the other hand, decreased summer discharges and decreased daily minimum discharges may lead to increased sedimentation in the channels of the Rhine system, because these decreased discharges coincide with increased sediment production on the slopes of the Rhine basin due to more intense and more frequent local summer thunderstorms under a warmer climate.

A first semi-quantitative approximation of the impact of climate change on sediment production in the Rhine basin has been made by Van der Drift et al. (1994). From this it appears that sediment production is very sensitive to climate warming. It is therefore recommended to investigate more quantitatively the effect of climate change on the processes, factors and rate of soil erosion in the sediment contributing landscape units of the Rhine basin.

8. TRANSPORT AND SEDIMENTATION

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Abstract

Erosion, transport and deposition of fine suspended sediments are both directly and indirectly influenced by changed climate conditions. Changes in sediment transport rates were studied using sediment rating curves in combination with flow duration curves, developed using the BaU-climate scenario and four sediment transport scenarios. All sediment transport scenarios show that an increasing part of the yearly sediment load will be transported at discharges over 4000 m^3/s: about 20% under present climate conditions increasing to about 40% when climate changes in accordance with the BaU-scenario.

Three aspects of floodplain sedimentation have been studied: (1) past and present sedimentation rates, (2) the impact of climate change on future sedimentation rates and (3) heavy metal pollution of sediment.

Floodplain sedimentation shows a high variability in time and space. Depending on site characteristics, present sedimentation rates range between 0.5 and 15 mm per year. At the beginning of floodplain formation, sedimentation rates probably were 3 to 4 times as high as at present. A climate change according to the BaU scenario will lead to a considerable increase in floodplain sedimentation rates in The Netherlands. Depending on the floodplain morphology, however, local changes in sedimentation rates will vary strongly; the expected increase will therefore range between 1% and >100%. The quality of the sediment is still a matter of concern. Although the heavy metal contamination has considerably decreased since 1970,

accelerated future sedimentation will accumulate considerable amounts of pollutants on the floodplains in The Netherlands.

8.1 Introduction

The expected climatic change will affect erosion, transport and deposition of suspended sediments of the river Rhine. Concerns are not only related to the impact of environmental and climatic changes on transport and sedimentation of suspended sediments, but also to transport and deposition of sediment associated pollutants.
Within the scope of the National Research Program (NRP 1) the impact of climate change on discharge, production, transport and sedimentation of suspended sediment by the river Rhine have been studied. The BaU-best scenario as given by Kwadijk (1993) was used to represent future climate conditions.
The impact of climate change on the hydrology of the river Rhine was studied by Kwadijk (1993) and Parmet et al. (Section 6). The study on the effects of climate change on the suspended sediment budget of the river Rhine can be subdivided in three stages. (1) Erosion or production of sediment, that can subsequently be transported into the river. Van der Drift identified the major source areas of the suspended sediment transported by the river Rhine. He also studied the effect of climate and land use change on soil erodibility. (2) A sediment transport stage, during which the sediment particles are transported downstream. (3) Sedimentation in the lower course of the river and the delta area and, during high discharge periods, on the embanked floodplains along the river.

A rough estimate of changes in sediment production by soil erosion was obtained by using the USLE rain erosivity factor in combination with the BaU climate scenario (Section 2) and land use scenario (Section 3). This study was carried out by Van der Drift, Middelkoop and Asselman (1994).
Transport and deposition of suspended sediment were investigated in two separate NRP studies which are reported here.
In the first project, carried out by Asselman, the relation between suspended sediment transport rates and discharge is investigated. The objectives of this study are:

- to investigate the processes of sediment transport through the river Rhine,
- to assess the effect of climate change on suspended sediment transport rates, depending on changes in discharge and sediment supply to the rivers.

In de second project, carried out by Middelkoop, the sedimentation on the embanked floodplains is investigated. Past and present sedimentation rates are reconstructed using various methods, and the possible effects of climate change on future floodplain sedimentation are assessed. The objectives of this study can be summarized as follows:

- Assessment of the rate of sedimentation on the embanked floodplains in The Netherlands in relation to flood-frequencies during the past decennia, and centuries.
- Assessment of quantitative relationships between (1) floodplain morphology, (2) the characteristics of flood periods and (3) sedimentation rates.
- Evaluation of possible effects of climate change on future floodplain sedimentation.

8.2 Methods

Transport of suspended sediment

The amount of fine suspended sediment (wash load) transported by the river Rhine depends on the availability of loose material and to a lesser extent on the capability of the river to transport this material. Unlike bed material load, wash load is a non-capacity load, which implies that sediment transport rates cannot be calculated using stream power related transport formulas. Instead, the so-called rating curve technique was used to study the effect of changes in discharge on the amount of suspended sediment transported through the river.

A sediment rating curve describes the average relation between discharge and suspended sediment concentration. This relation is often described by a power function. In this study a power function with additive constant term was used:

$$C = P + a^* Q^b$$

where c is suspended sediment concentration (mg/l), Q is river discharge (m^3/s) and a, b and p are regression coefficients.

The sediment rating curves can be used to obtain information on the availability of sediment in a certain area in combination with the erosive power of the river itself. Steep rating curves (low a- and high b-values) are characteristic for river sections with little sediment transport taking place at low discharge. An increase in discharge results in a large increment of suspended sediment concentrations, indicating that either the power of the river to erode material during high discharge periods is great, or that important sediment sources become available when the water level rises. Flat rating curves are characteristic for river sections with intensively weathered materials or loose sedimentary deposits, which can be transported at relatively low discharges. The constant p-coefficient can be seen as a background concentration, a minimum concentration of suspended sediment occurring at very low discharges.

In this study, sediment rating curves were developed for various locations along the river Rhine, using the daily measurements of water discharge and suspended sediment concentrations, measured by the Bundesanstalt für Gewasserkunde (BfG), Germany. The sediment rating curves were combined with flow duration curves to obtain sediment discharge curves, showing the effectiveness of different discharge intervals in transporting suspended sediment.

Changes in the sediment discharge regime were studied using the changes in monthly discharges of the river Rhine given by Kwadijk (1993) and Parmet et al (Section 6). A relationship between monthly and daily water discharges was obtained following the method used by Kwadijk and Middelkoop (1994). The newly obtained flow duration curve was combined with different sediment rating curves to obtain the sediment discharge curves. Different sediment rating curves were used, corresponding to assumed changes in sediment production in the Rhine basin. A rough estimate of long term average changes in suspended sediment production by soil erosion in the Rhine basin under BaU climate and land use conditions was made using the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1978). It was assumed that only arable land substantially contributes to the production of fine sediment by soil erosion. The effect of climate change is calculated from changes in the rain erosivity factor (R) in the USLE. The estimations of future soil erosion under changed rain erosivity are therefore assessed by changes in both the total amount and intensity of rainfall under the BaU climate scenario. Future rainfall intensities are calculated from changes in temperatures according to Klein Tank & Können (1993). The effect of changes in land use (Veeneklaas et al., 1994; Section 6) on soil erosion is calculated from the expected changes in the total area of arable land. The results are described in Van der Drift et al. (1994); the changes in annual suspended sediment load that are used for the sediment rating curves are shown in table 8.1.

For Rees, near the Dutch-German border (figure 8.1), the following sediment transport scenarios were used:

1) Sediment loads are determined by hydraulic properties of the river, sediment production in upstream areas has no direct effect. 1a) The present rating curve remains valid under changed climate conditions; total yearly sediment load will change. 1b) Background concentrations will change under changed climate conditions; total yearly sediment load remains constant.
2) Sediment loads are determined by the erosion rates in upstream parts of the river basin. Changes in erosion rates are influenced only by changes in precipitation and temperature, no land use scenario is used.
3) Sediment loads are determined by the erosion rates in upstream parts of the river basin. Differences in precipitation, temperature, and land use are taken into account.
4) Sediment loads are determined by the erosion rates in upstream parts of the river basin. Changes in erosion rates are the result of changes in land use. No climate change is taken into account. This scenario is used as a reference scenario to evaluate the effect of climate change under changed land use conditions. In this case land use changes are assumed to be independent from climate change.

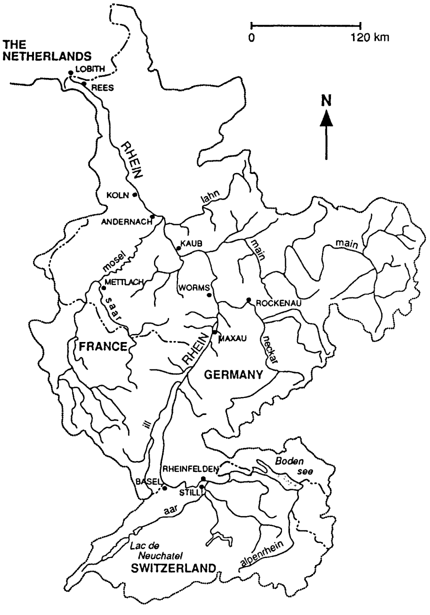


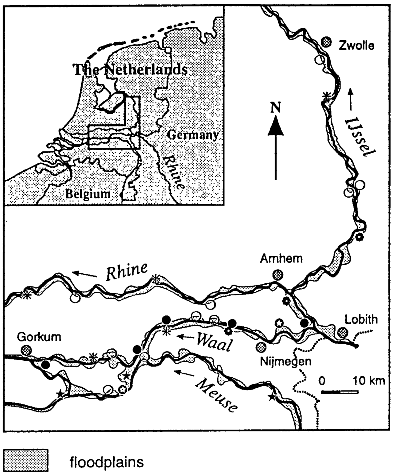
Figure 8.1
Location of the gauging stations

Analysis of sediment from dike-breach ponds

For the reconstruction of temporal variations in sedimentation rate during the past 200 - 300 years, sediment accumulated in dike-breach ponds was analyzed. These sediments can have a thickness of more than 5 m. They often show a lamination of light and dark coloured humic clay. These laminations are believed to represent (yearly) floods. In order to correlate these laminae to floods and minor climate changes in the past, they were dated using the Pb-210 method. Analysis of the heavy metal contamination of samples from the dated sediment profiles allowed to make a reconstruction of the pollution history of the river Rhine.

Floodplain sedimentation rates on various time scales

For a better interpretation of expected future changes in floodplain sedimentation rates, the spatial and temporal variability of the present and past sedimentation rates were investigated first (figure 8.2).



symbol on map	old river maps	Heavy metals	sediment traps
●	X	X	X
❂	X	X	
✪	X		X
○	X		
✱		X	
★			X

X = method applied at floodplain section

Figure 8.2
Study area and location of investigated floodplains

A. Present sedimentation rates. Present floodplain sedimentation rates and their spatial variability were measured after the two floods of 1993 and one in 1994 using about 800 sediment traps made of artificial grass. In the laboratory, the (dry) sediment from the traps was weighed, and the grain size distribution and organic matter content were determined. The results from the individual traps were interpolated to create raster maps of sediment accumulation, sand content and organic matter content. The patterns shown on the maps were correlated with floodplain morphology and sedimentation mechanisms (Asselman & Middelkoop, 1993).

B. Sedimentation rates during the past decennia. In several floodplain sections with different elevations and distances to the main channel, soil samples from vertical profiles were collected and their heavy metal content was measured. The heavy metal content of floodplain soils was related to floodplain morphology and flood frequency. The sedimentation rates during the past 50 - 100 years were reconstructed by comparing the heavy metal profiles in the floodplain soils with the pollution history of the Rhine (determined from the dike-breach ponds). In addition, the sedimentation rates of several profiles were assessed using the Pb-210 method.

C. Sedimentation rates since the formation of the embanked floodplains. Old river maps provide a rough indication of the beginning of sedimentation on the enclosed floodplains. The total amount of accumulated sediment can be assessed by means of corings. Flood durations can be calculated from records of historic water levels. Using this information a simple model was made to estimate the average yearly sedimentation on several floodplains (Middelkoop & van der Perk, 1991).

Assessment of the impact of climate change on floodplain sedimentation rates

A. Assessment of the impact on floodplain inundation times. Using the RHINEFLOW model, the changes in monthly Rhine discharges were assessed for the BaU scenario (Kwadijk, 1993; Parmet et al., Section 6). From the relationship between monthly discharges and daily discharges, changes in peak discharge probabilities and exceedance times were calculated (Kwadijk & Middelkoop, 1994). These were used to assess future floodplain inundation times.

B. Assessment of local sedimentation rates using a sedimentation model. The effect of climate change on the sedimentation rate on one floodplain was investigated using the (2-dimensional) WAQUA-DELWAQ model of Rijkswaterstaat (Dutch Ministry of Transport, Public Works and Water Management). Calibration of the model was carried out by simulating the flood of January 1993 of which the sedimentation rates were measured using the sediment traps. Also, the average sedimentation rates over the past 50 years reconstructed from heavy metal profiles of the floodplain soil were used to calibrate the model. The sedimentation rates under changed climate conditions were assessed by using the sediment discharge curves in correspondence with the BaU climate scenario.

C. Sensitivity of large scale potential sedimentation rates.Complementary to the detailed model study for a small area using WAQUA-DELWAQ it was tried to estimate the sensitivity of floodplain sedimentation rates for the Rhine (Waal-branch) embanked floodplains as a whole. At this scale it is not possible to take physical flow and sedimentation processes into account. Instead, two estimators for potential floodplain sedimentation were introduced. The term potential sedimentation is used because the estimators do not calculate real sediment deposition, but they are a measure of the amount of sediment available for deposition. The first estimator calculates for each discharge interval the product of the corresponding (1) total floodplain area over which sediment flows, (2) the suspended sediment concentration and (3) the relative frequency of occurrence. The summed totals for all discharges gives the average yearly figure, expressed in $km^2*kg/m^3/yr$. The second estimator uses total volumes of water over floodplain areas and calculates the total average yearly load of suspended sediment present over floodplains, expressed in tons/yr.

The effect of the BaU discharge scenario and four sediment rating scenarios on the estimators has been calculated to investigate the possible impact on floodplain sedimentation.

8.3 Results

Transport of suspended sediment

The relationship between discharge and suspended sediment concentration shows considerable scatter. Some of this scatter can be the result of inaccuracies in the field or in the laboratory, seasonal effects, antecedent conditions in the river basin and differences between falling and rising stages. To reduce the scatter separate rating curves were developed after subdividing the data according to season, stage and wet or dry years. However, since this hardly improved the rating relationship, rating curves were developed using all data.

The sediment rating curves developed for various gauging stations are shown in figure 8.3. It can be seen that the steepness of the rating curve decreases in downstream direction, indicating that near the Dutch-German border large quantities of fine material are available for transport at relatively low discharge. The importance of high discharge on suspended sediment transport decreases in downstream direction.

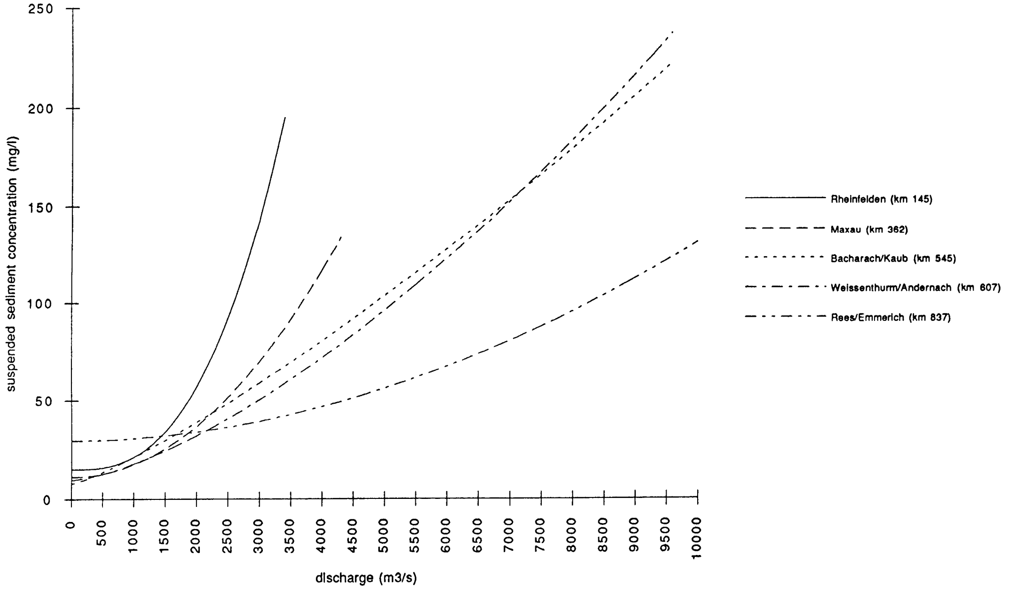


Figure 8.3
Sediment rating curves developed for various gauging stations along the River Rhine

Sediment discharge curves for the river Rhine near Rees were developed using the flow duration curves in combination with the sediment rating curves developed for present and future climate conditions. The sediment discharge curves are shown in figure 8.4. The results of the different sediment transport scenarios are also given in table 8.1.

Table 8.1
Sediment transport rates using four sediment transport scenarios

scenario	P	Total load % and (Mt/yr)	>4000 % and (Mt/yr)	>6000 % and (Mt/yr)
Present	29	100 (3.09)	20 (0.62)	5 (0.15)
1a	29	115 (3.55)	35 (1.24)	17 (0.60)
1b	24	100 (3.09)	37 (1.14)	18 (0.56)
2	32	122 (3.77)	35 (1.32)	16 (0.60)
3	15	78 (2.41)	42 (1.01)	20 (0.48)
4	18	71 (2.20)	22 (0.48)	6 (0.13)

p = background concentration (mg/l)
total load = % of present total yearly sediment transport
>4000 = percentage of total sediment load transported at Q>4000 m^3/s
>6000 = percentage of total sediment load transported at Q>6000 m^3/s

Steepness of the rating curve is kept constant with a = 1.96*10-5 and b = 1.93

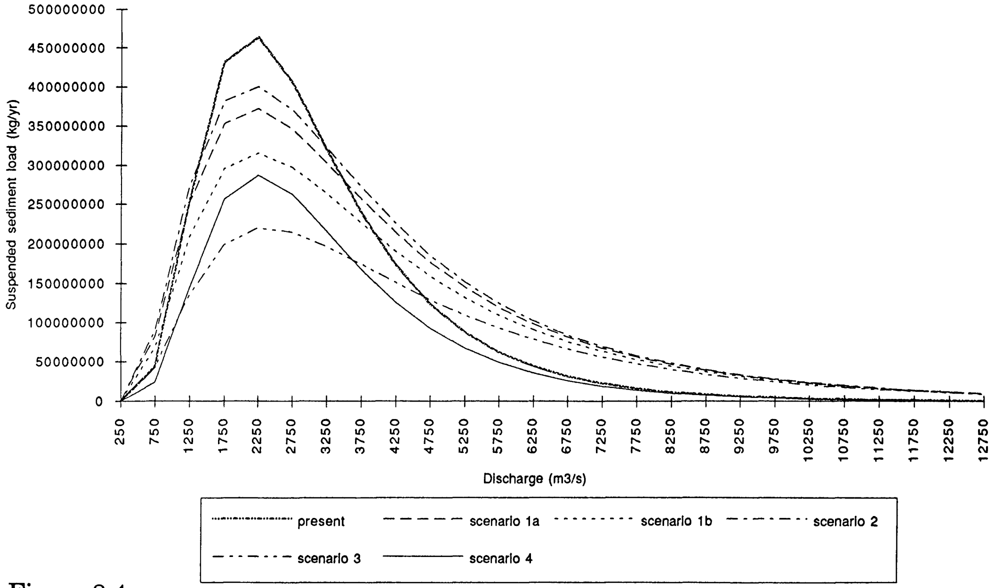


Figure 8.4
Sediment discharge curves developed for Rees according to three sediment transport scenario's

Scenario 1. According to the first sediment transport scenario, suspended sediment concentrations only depend on hydraulic properties of the river and thus on discharge. The effect of climate change can therefore be simulated using the sediment rating curve based on measurements of the last 15 years in combination with the flow duration curve according to the BaU scenario. The resulting sediment discharge curve shows that more suspended sediment will be transported both at very low discharge ($Q < 1500$ m^3/s) and at high discharge when inundation of low lying floodplains occurs ($Q > 4000$ m^3/s). If the present sediment rating curve is used (scenario 1a), total suspended sediment load will increase by 15%. If the total load remains the same (scenario 1b), background concentrations will decrease from 29 to about 24 mg/l.

Scenario 2. When changes in soil loss due to climate change are investigated using the BaU scenario for changes in rainfall amounts and rainfall intensities while land use is assumed to remain unchanged, sediment production will increase by 22% (van der Drift et al., 1994). The increased sediment load can result in higher background concentrations, occurring at low discharges. If the steepness of the sediment rating curve remains the same, background concentrations will increase from 29 to about 32 mg/l.

Scenario 3. When changes in soil loss under the BaU climate scenario are combined with a land use scenario with a 23 to 48% decrease in area of arable land, sediment production will decrease by 22%. This means that even if the steepness of the rating curve changes, the background concentration will decrease. This can be explained by the trapping of sediment behind weirs. During summer discharge will decrease, which might result in increased sedimentation behind weirs during summer time and lower base flow concentrations near Rees. During the winter, more high discharge periods will occur and much of the sediments deposited behind weirs will be flushed out, leading to higher concentrations in the river during high discharge events, as shown by the increased value of the b-coefficient. If the steepness of the rating curve changes, background concentrations will decrease to 18 mg/l or less. If the steepness of the rating curve remains the same, expressed by the unaltered values of a and b, the background concentration (p) will decrease to 15 mg/l.

Scenario 4. In scenario 4 the effect of changes in land use without a climatic change is studied. As a result of a 25 to 42% decrease in arable land, the total suspended sediment load will decrease by about 29%. If the steepness of the rating curve remains the same, background concentrations will be about 18 mg/l. A similar background concentration was found for scenario 3. The most important difference occurs in the sediment discharge curve. According to scenario 4 only 22% of the total sediment load (0.48 Mt/yr) is transported at discharges over 4000 m^3/s. When changes in land use occur in combination with changes in climate (scenario 3) about 42% of the total yearly load (1.02 Mt/yr) is transported at discharges of 4000 m^3/s or more. This difference is mainly the result of changes in the flow duration curve. High discharges will occur more often under BaU climate conditions than under present climate conditions.

From the scenarios is can be concluded that the expected change in land use has a stronger impact on the yearly production of suspended sediment than the BaU climate scenario. However, due to the changes in the flow duration curve, a climate change will have a much stronger effect on possible floodplain sedimentation. The effect of climate change under changed land use scenario will be about the same as under present land use conditions.

Analysis of sediment from dike-breach ponds

Although the sediment shows a clear lamination, it is difficult to correlate this to individual floods and hence to fluctuations in flood frequencies. This is because local sedimentation rates are the results of a combination of flood duration, inundation depth, sediment concentration and local flow patterns. It is virtually impossible to reconstruct these in detail for historic times.

Using historic dates, Pb-210 dates, palynological information and variations in sediment compaction a time/depth curve of the sediment could be made. Using this as time control the heavy metal pollution of the Rhine sediment during the last 200 years was reconstructed (figure 8.5). This diagram shows that the heavy metal pollution strongly increased during the first half of this century; maximum pollution occurred between 1960 and 1970, since 1970 the heavy metal pollution has strongly decreased.

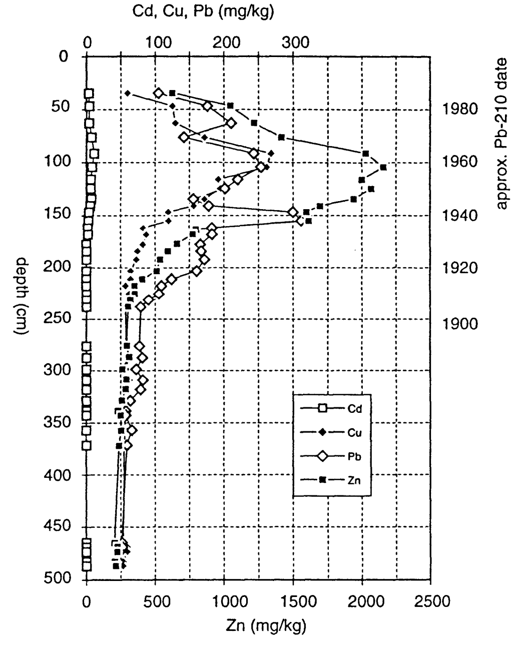


Figure 8.5
Heavy metal pollution history of the river Rhine reconstructed from a dike-breach pond near Wamel

Floodplain sedimentation rates on various time scales

A. Present sedimentation rates. The sediment accumulation maps show clear patterns in spatial variability (figure 8.6). During a flood, large amounts of sandy sediment with low organic matter content are deposited on the levees. The sediment accumulation decreases exponentially with distance from the river. This

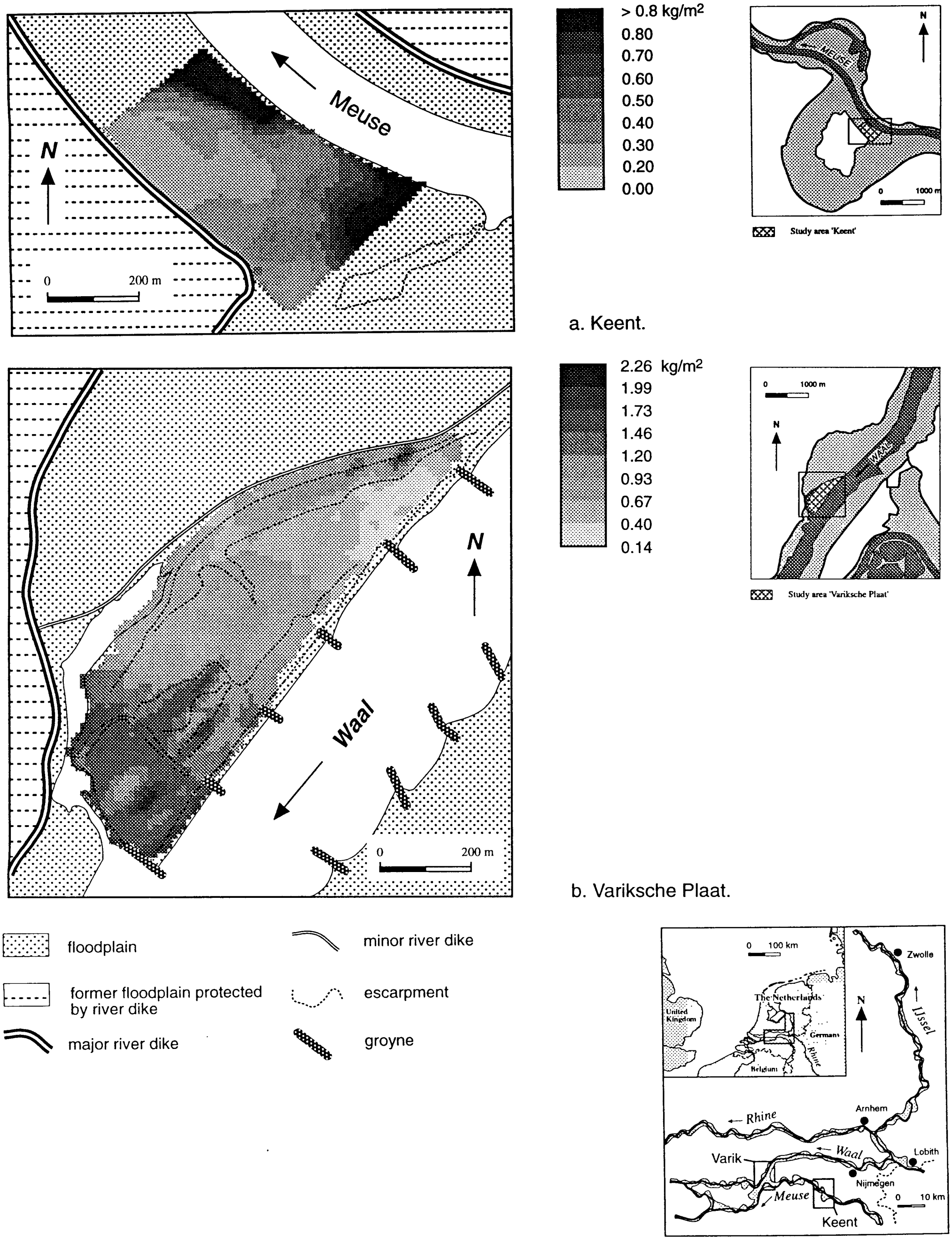


Figure 8.6
Estimated sediment accumulation after block kriging. Grid cell size = 10 x 10 m2

gradient is mainly caused by the amounts of deposited sand; no gradient was found in the amounts of silt and clay. The amounts of sand deposited just behind the levee show a high spatial variability. If a floodplain has been completely submerged for several days, local depressions have almost no effect on the sediment deposition.

The amounts of sediment deposited on different floodplains can vary considerably. Observed average values after the flood of december 1993 range between 1.0 and 6.6 kg/m2, equivalent to 0.8 respectively 5.4 mm. These differences between floodplains seem mainly related to the flow pattern of the water during inundation. During minor floods, when a floodplain is inundated only during a few days, the pattern of sediment accumulation is much more related to local differences in elevation and inundation times than during large floods.
The amount of deposited sediment is far less than proportional to the magnitude of the flood. This implies that minor floods contribute considerably to the yearly floodplain sedimentation rate.
From the results of the individual floods, the present average yearly sedimentation rates will be estimated for different floodplain sections. This part of the study is still in progress.

B. Sedimentation rates during the past decennia. The heavy metal profiles obtained from the floodplain soils generally have the same shape as the pollution curve reconstructed from the dike-breach pond sediments. Profiles from floodplains with high sedimentation rates have a higher pollution in the upper 10 cm and have a higher total pollution. Also the maximum concentration is greater and is found at greater depth. The results show that the total soil pollution can be very different from the pollution in the upper 10 cm. A one-dimensional sedimentation model is being developed that simulates the floodplain sedimentation with contaminated sediments. Using this model the sedimentation rates will be reconstructed. The average sedimentation rates during the past decades obtained from the Pb-210 samples range between 1.6 and 0.1 cm/yr.

C. Sedimentation rates since the floodplain formation. This method applies to lateral bars and can be used in a limited number of undisturbed floodplains. At the beginning of the floodplain formation the sedimentation rates varied between 1 and 3 cm/year, which is 3 to 4 times as great as at present. Two examples are shown in table 8.2.

A. Klompenwaard: 1800 - 1990

year	elev. (m a.s.l.)	sed. rate (mm/yr)
1800	10.6	16.0
1850	11.2	11.0
1900	11.7	7.6
1950	12.0	6.2
1990	12.3	4.8

B. Variksche Plaat: 1860 - 1990

year	elev. (m a.s.l.)	sed. rate (mm/yr)
1860	4.5	30.0
1900	5.4	18.0
1950	6.1	11.0
1990	6.5	8.5

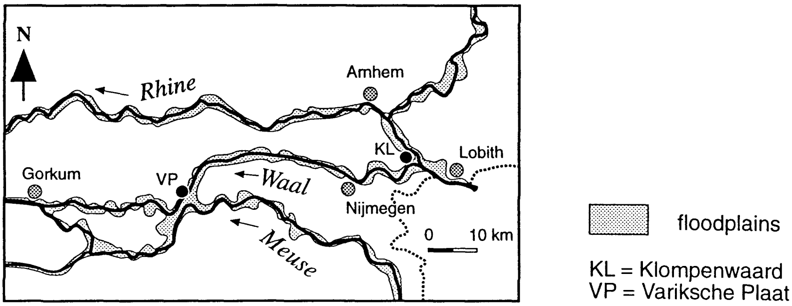


Table 8.2
Reconstruction of average yearly sedimentation rates using historic data; two examples

Assessment of the impact of climate change on floodplain sedimentation rates

A. Assessment of impact on floodplain inundation times. The effects of climate changes on the Rhine peak discharge frequencies and exceedance times according to the AP and BaU scenarios are given in Section 6. The BaU scenario causes a significant increase in inundation times of floodplains.

B. Assessment of local sedimentation rates using a sedimentation model. A proper calibration of the WAQUA/DELWAQ model requires more data on actual sedimentation than those obtained of the flood of January 1993, and preferably for larger areas than the Variksche Plaat. Therefore, also the sediment measurements of the December 1993 flood will be used for calibration. Preliminary results of the model indicate that the sedimentation rates on the Variksche Plaat under the BaU climate scenario increase by only 1% if the sediment concentration of the Rhine only depends on hydraulic conditions. Sedimentation rates increase by almost 20% when increased sediment production is taken into account. The effect of climate change for this particular floodplain seems to be insignificant. The main reason for this is that in floodplains directly bordering the main channel only minor amounts of sediment are deposited during high discharges since the flow velocities are then too high for sedimentation. The increase in sedimentation rates will be larger on floodplains that are separated from the main channel by a summer dike and where relatively large amounts of sediment are deposited during high discharges.

C. Sensitivity of large scale potential sedimentation rates. The BaU scenario has a strong impact on the potential floodplain sedimentation (figure 8.7 and 8.8). According to the estimator using sedimentation areas, potential sedimentation rates will increase by a factor 1.5 to 2, depending on the sediment rating scenario. The effect on the estimator using sediment volumes is even larger: potential sedimentation rates will increase by a factor 1.7 to 3. When scenario 4 (only land use change) is taken as a reference, potential sedimentation may increase by a factor 2.5 respectively 4.5. As demonstrated by the WAQUA/DELWAQ model study of the Variksche Plaat, the increase in the amounts of sediment that really will be deposited may be less large. This strongly depends on the morphological properties of the floodplain sections. For a proper estimate a further analysis of the sedimentation process using sediment traps and models such as WAQUA/DELWAQ is required in different types of floodplains.

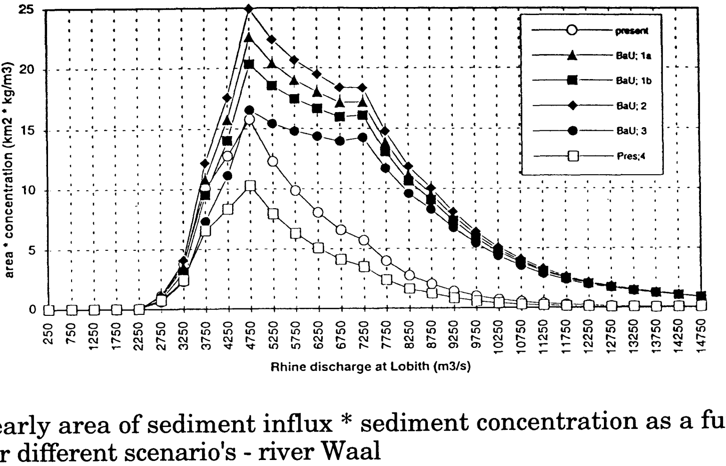


Figure 8.7
Expected yearly area of sediment influx * sediment concentration as a function of discharge for different scenario's - river Waal

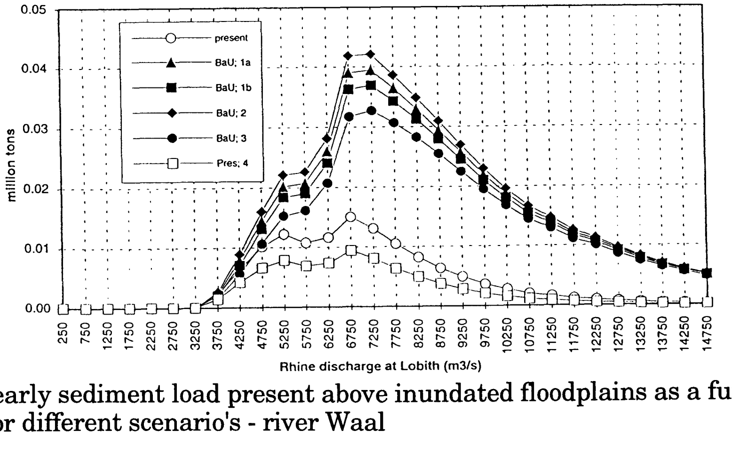


Figure 8.8
Expected yearly sediment load present above inundated floodplains as a function of discharge for different scenario's - river Waal

8.4 Implications

According to all sediment transport scenarios a larger part of the yearly sediment load will be transported at discharges over 4000 m3/s, when inundation of low lying floodplains occurs. Under present climate conditions about 20% of the yearly sediment load is transported at discharges over 4000 m3/s, this will be about 40% when climate changes according to the BaU scenario. Under present climate conditions about 5% of the total sediment load is transported when all floodplains bordering the Dutch part of the river are inundated (Q>6000 m3/s); this will be over 15% when climate changes.

If no measures against soil erosion are taken by reducing the area of arable land or by soil conservation programmes, the production of sediment will increase. Increased, sediment production will lead to about 20% higher concentrations of suspended sediment at low discharges.

When the area of arable land decreases, background suspended sediment concentrations will decrease by some 40%.

The amounts of suspended sediment transported at discharges when all floodplains are inundated is hardly affected by the expected changes in land use. The increase in sediment load, transported at high discharge is mainly the result of changes in the discharge regime.

Floodplain sedimentation is a complex process. It depends on floodplain characteristics, discharge frequency distributions and sediment concentrations, and therefore shows a high variability in time and space. Depending on site characteristics, present sedimentation rates range between 0.5 and 15 mm per year.

Present sedimentation rates are 3 to 4 times as low as they were in the past when the floodplain surface was 1 to 2 m lower and flooding occurred more frequently. This implies that removal of summer dikes and lowering of floodplain surfaces as proposed in nature rehabilitation plans will strongly increase sedimentation rates.

The effects of climate change on floodplain sedimentation, as evaluated using the BaU scenario can be considerable. This is mainly caused by an increased frequency of high discharges. As the relationship between effective discharge and the area of inundated floodplains is non-linear, even minor changes in discharge and sediment concentrations will have a strong effect. As a result, the potential floodplain sedimentation is very sensitive for the BaU discharge and sediment rating scenario conditions. The effective sedimentation rates may be different, depending on the morphology and type of floodplain. On floodplain sections directly bordering the main channel and without a summer dike, changes in sedimentation rates are relatively unimportant. However, the effect on floodplains that are situated behind a summer dike, is expected to be relatively high.

As it was found that floodplain sedimentation is highly variable in space and during individual floods, predictions on future sedimentation rates cannot yet be done with high accuracy.

Further analysis on the effective sedimentation on different types of floodplain sections is therefore required.

Apart from the sediment quantities, sediment quality is a matter of concern. A reconstruction of the heavy metal pollution of the river Rhine during the past century shows that maximum pollution occurred between 1960 and 1970. The present distribution of heavy metals in floodplain soils is related to this pollution history and the floodplain sedimentation in the past. At many locations the soil quality of the upper 10 cm gives an underestimation of the total pollution of the whole profile. Although the heavy metal content has considerably decreased since 1970, an accelerated sedimentation will still accumulate large amounts of heavy metals on the floodplains in The Netherlands. As average sedimentation rates on most floodplains are in the order of 1 mm/yr, the quality of the upper 50 cm of the floodplain soils will only little improve by the accumulation of sediment of improving quality during the forthcoming century.

9. ECONOMY, SAFETY, ENVIRONMENT

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9.1 Introduction

In the following pages the results of the hydrology-related projects in the NRP, and their implications for economy, safety and environment, are compared with the results and conclusions of earlier studies. The objective of this comparison is to evaluate whether the NRP-sponsored research has led to changed insights into the impacts of hydrology-related impacts of climate change on the economy, safety and environment in The Netherlands.

During the period when IPCC produced its First Assessment Report a comprehensive study was undertaken in The Netherlands to assess the Impacts of Sea Level Rise on Society (ISOS). The ISOS study (Peerbolte et al., 1991) focused largely on sea level rise, but attempted to assess the impacts of changes in hydrology on various aspects of the economy, safety against flooding and the environment as well. The study attempted to integrate data, knowledge and modelling results available in 1988-1991 to produce an assessment of the impacts of climate change for The Netherlands that can be considered as a state-of-the-art review at that point in time; as such it is used in the following pages as a baseline against which the progress made through the NRP programme can be evaluated.

It has to be noted at the outset that the approach adopted in the ISOS and NRP studies is quite fundamentally different. The former study made relatively quick and dirty scenario-assumptions for local changes in climate and for a series of physical (intermediate) effects of such changes, e.g. on discharge of the River Rhine, and subsequently attempted to estimate socio-economic impacts resulting from these changes. Impacts were expressed, where possible, in monetary terms for damages such as production losses in agriculture, flooding damages for industry, additional costs of provision of cooling for power plants, and increased costs of water management measures such as pumping drainage water.

The hydrology related NRP studies focus largely on the development of regional climate change scenarios (Section 2) and the direct physical effects of these changes in terms of soil erosion, river discharge, sediment transport, sediment deposition, saline seepage and the hydrology of forests. The hydrology-related NRP studies do not assess the socio-economic impacts of these physical effects directly, with the exception of the analysis of changes in agricultural production caused by changes in temperature, evaporation, precipitation and CO_2-concentrations.

9.2 Climate scenarios

One of the more important steps forward in the last few years is the improved regionalization of the climate change scenarios. Both earlier studies as well as the NRP studies are based on the IPCC Business as Usual (BaU) scenario, but the regionalization of the hydrology-related climate variables is quite different. For comparison the scenarios used in the ISOS-study are presented hereafter, together with the scenarios on which the NRP studies are based. One ISOS-scenario is the so-called Average (AV) scenario in which all variables, including hydrology-related variables, have their expected values. Another scenario, in which the estimated standard deviations were deducted from the expected values for all variables, is referred to as the Unfavourable (UNF.ALL) scenario.

The hydrology related NRP-studies refer to either the regional climate scenarios for The Netherlands developed in NRP (Section 2) or the scenarios for the Rhine Basin developed by Kwadijk (1993). These are also expected values and should therefore be compared with the AV scenario in ISOS. Both scenarios are presented in Table 9.1, together with the two earlier scenarios.

Table 9.1
Comparison of regionalized climate change scenarios used in the hydrology related NRP studies as well as in earlier studies

Variables	ISOS AV	ISOS UNF.ALL	NRP	Kwadijk
Ta	+ 3	+ 3	+ 3	+ 3.5
Tw	+ 3	+ 3	* 2.3-3.7	+ 4.3
Ts	+ 3	+ 3	* 2.3-3.7	+ 2.9
Pa	+ 10%	-	+ 13%	+ 11%
Pw	+ 10%	+15%	* 3%-21%	+ 19%
Ps	+ 10%	+ 5%	* 3%-21%	+ 4%
Qw	+ 5%	+ 10%	** + 15%	
Qs	- 5%	- 10%	** - 10%	
Ea=Ew=Es	+ 10%	+ 15%		
SLR	0.6	0.85		

* monthly values
** computed values from NRP studies (Parmet et al., 1994)
Where:
Ta = average annual Temperature increase in degrees C
Ts = summer T increase in degrees C
Tw = winter T increase in degrees C
Pa = average precipitation change in %
Ps = summer precipitation change in %
Pw = winter precipitation change in %
Qs = summer river discharge change in %
Qw = winter river discharge change
SLR = sea level rise in m
Ea = average annual evaporation change in %

As can be seen from Table 9.1, the changes in precipitation assumed in the recent scenarios (Section 2) are considerably greater than in the earlier (ISOS-AV) scenario; even greater than in the scenario that was considered "extreme" a few years ago (UNF.ALL). Similarly, the expected changes in river Rhine discharge resulting from the recent NRP RHINEFLOW study considerably exceed the average changes expected earlier (AV scenario). In addition, the NRP studies (Section 6) conclude that the frequency of low flow months (Q< 1000 m3/s) increases with 60%. The conclusion can be drawn from the scenarios presented above that the regional climate change studies undertaken in recent years have shown that the hydrological changes associated with the IPCC-BAU scenario are considerably greater than expected before. Consequently, the hydrology-related impacts of climate change on the economy, safety and the environment can also be expected to be relatively more important than estimated before.

9.3 Impacts on safety against flooding

In the ISOS study it was assumed that the design discharge used for flood protection infrastructure (a discharge of 16,500 m3/s at Lobith, with a recurrence interval of 1250 years) would increase 10%. This resulted in increased design dike crest levels for the river dikes that varied between 0.1 and 0.5 m for different dike sections to maintain the same safety against flooding. The cost of raising river dikes in the non-tidal part of the country (necessitated both by sea level rise and increased river discharges) was estimated to be in the order of 2,500 million guilders over a 100 year period. The cost of raising sea and river dikes was the largest direct economic impact of sea level rise determined in the ISOS-study.

The NRP RHINEFLOW study concludes that the average winter discharge increases 15% (Qw= +15%), but — since only a 25 years period was simulated — does not allow conclusions to be drawn concerning changes in discharges at frequencies relevant for flood analyses, e.g. discharges with a recurrence interval of 1250 years (Section 6). In a related study, Kwadijk and Middelkoop (1994) used the RHINEFLOW model to assess the probability of exceedance for discharge peaks under possible future climate conditions. For peak discharges relevant for flooding of floodplains (up to Q= 6.500 m3/s) they found that a precipitation increase of 20% leads to a 30% higher two-year peak discharge. For larger design discharges, used for the design of flood protection structures, reliable results could not be obtained because the length of the discharge record was too short. This implies that the hydrology-related NRP studies have not, so far, improved the assessment of flood-safety related impacts. Further analyses of the changes in the peak discharges of the River Rhine are therefore recommended.

9.4 Economic impacts

Impacts on agricultural production and land use

The NRP study (Section 3) analyzed changes in crop yield potential for a time horizon of 2040-2050 with a biophysical simulation model (WOFOST) for Ps=0% en PW=+10%, Ts=1.5, Tw=2, double CO2 concentrations, and computed (Penman) evaporation rates (Ea= +15%). It concludes that the changes would result in average increases in yields of wheat, grass, sugarbeets and corn on sandy soils in the Rhine river basin of 40, 33, 25 and 12 %, respectively. Based on analysis of autonomous developments such as population growth, agricultural production levels and developments in the world and EU market, land use patterns have been simulated, with and without climate change. Without climate change, the range of land use scenarios for the Rhine Basin in the decade 2040-2050 shows that the land used for agriculture will decrease by 0 to 3 million hectares. With climate change, land used for agriculture decreases an additional 0.2 million hectares.

Both earlier studies and analysis carried out in the NRP (Section 5) conclude that possible increases in saline seepage through the groundwater due to sea level rise are negligible.

Parmet et al. (Section 6) conclude that the summer discharge of the River Rhine would decrease by about 10% and the number of low flow months (Q< 1000 m3/s) increases with about 60%. It has not been analyzed in the NRP what the surface water related implications of these drier summer conditions are, but these could be considerable. The analyses of earlier studies concerning climate change impacts on agricultural production focused on surface water management related issues, including agriculture drought damage, agriculture salinity damage, sprinkler irrigation cost; (discharge) pumping capacity and cost. Conclusions were, for instance, that hydrological dryness influences drought damage substantially, e.g., Ps=-7% (and assumed Es=+15%) resulted in 38% increase of drought damage cost from about 350 to about 500 million guilders per year (Peerbolte et al., 1991). It was also concluded that reductions in average summer discharge of the River Rhine, e.g., Qs=-7%, had only minor impacts on agricultural production.

Summarizing, the NRP studies have concluded that there is a potential for significant increases in agricultural production as well as a potential of significant increases in drought damage. From a perspective of the socio-economic impacts on agriculture, the forecasted increase in productivity could increase the comparative advantage of agriculture in The Netherlands, but this will depend on a host of other factors as well (e.g., surface water related drought damages, and water management costs). The surface water related impacts of the considerably lower summer discharges of the Rhine have not been investigated in the NRP studies, but based on earlier studies it is expected that these could be quite significant for The Netherlands.

Increased costs of electricity production

The ISOS study concluded that the additional costs of electricity production of a decrease in summer discharge of the River Rhine (Qs=-7%) would be in the order of 6 million guilders per year. In Section 6 it is concluded that the average reduction in summer discharges could be higher (Qs=-10%) and that the frequency of low flow months, which can be critical for design of the cooling system, increases considerably. The additional costs of electricity production are therefore likely to be significantly higher than estimated in the earlier studies.

Water management costs

The larger decrease in average summer Rhine discharges, and increased frequency of low flow months, can also be expected to impact several surface water management factors, particularly the effort required to control the salinity intrusion through the Nieuwe Waterweg (harbour of Rotterdam), navigation, and flushing of polder areas. Increased costs for shipping have not been analyzed in the climate change impact studies to date. Through other studies it is known, however, that the costs for navigation increase rapidly when discharges decrease. Shipping costs in The Netherlands increase from 85 million guilders per week to 130 million guilders per week as the discharge decreases from 1600 to 1000 m3/s (Anonymous, 1990).

Flooding in floodplains

Earlier studies by Licht (1990) estimated that for SLR= 0.85, Qs=-10%, en Qw=+10%, the expected annual economic losses for the brick industry are in the order of 2 million guilders per year due to increased flooding, whereas for dairy farming the increased flooding in winter is more or less compensated by decreased flooding in summer. The NRP study results (Section 6) of Qs=-10% and Qw=+15% would probably result in somewhat higher losses for both the brick industry and dairy farming, but these impacts are still quite small.

Impacts on the environment

The NRP studies evaluated changes in the following variables that may, in turn, cause environmental impacts:

- sediment production (Section 7) and suspended sediment transport and suspended sediment deposition on embanked river floodplains (Section 8);
- hydrology of forests (Section 4).

Earlier studies for The Netherlands evaluated a number of climate change impacts on the environment, but most of these related to coastal environmental aspects. Where, for instance, the ISOS study did look at environmental impacts (impact of flooding on natural areas in river floodplains; decreased biomass phytoplankton and chlorophyll in fresh water ecosystems), the assumed changes in hydrology were too small to determine significant impacts on the environment.

The NRP studies showed that sediment production in the River Rhine catchment area may increase by about 20% due to climate change (Section 8), but this increase will be more than balanced by autonomous land use changes that cause a decrease in sediment production. The NRP studies also show that a much higher part of the suspended sediment will be transported at higher discharges, which will lead to a considerably higher deposition of suspended sediment on the embanked floodplains (Section 8). If this sediment remains as polluted as it has been during the last decades than this would lead to a buildup of pollutants on the floodplains which will have serious consequences for the environment. Fortunately, there is a trend towards improving sediment quality in the River Rhine that may mitigate this potential impact. The studies on the hydrology of forests shows that increasing CO_2 concentrations may lead to lower evapotranspiration and hence reduced drought damages in summer. Generally speaking, the value of the conclusions of these studies would increase if they were integrated into a common framework for analysis.

The changes in the hydrology-related climate variables that follow from the scenarios discussed above, as well as the computed changes in river discharge, are likely to have significant consequences for natural ecosystems, such as desiccation of floodplains in summer. Such ecosystem related consequences have not been looked at in the hydrology-related NRP studies, however.

9.5 Conclusions

The changes in hydrology-related climate variables that follow from NRP regionalized climate scenarios are significantly greater those assumed in earlier studies. NRP studies have analyzed the changes in average summer and winter discharges of the River Rhine, as well as the changes in the 2-year peak discharges and frequency of low flow months. The results of these studies show that the discharges of the River Rhine change considerably more than assumed earlier. Peak discharges at recurrence intervals relevant for analysis of impacts on flood safety have not yet been analyzed. Further research in this area is recommended.

NRP studies have shown that the expected changes in temperature, precipitation and CO_2-concentration have the potential for increased agricultural productivity in The Netherlands. The economic consequences of such changes also depend on changes in drought damages and water management costs. The hydrology related NRP studies have forecasted relatively greater decreases in average summer discharges of the River Rhine than assumed earlier, and significantly increased frequencies of low flow months. This is likely to have considerable impacts on drought damages in agriculture, water management costs, costs of navigation, and costs of electricity production. These surface-water related drought effects may well be the most important economic impacts caused by changes in hydrological climate variables.

Several NRP studies have assessed physical effects due to changes in hydrologic variables, such as sediment production, sediment transport and deposition, and hydrology of forests. The expected change in hydrology is likely to lead to increased sediment production, a larger deposition of sediment on the embanked floodplains, and a decrease in the evapotranspiration of forests. These physical effects are likely to have impacts on the environment, but these have not been estimated directly. It is recommended that the analysis of impacts of the various physical effects studied in the future hydrology-related NRP projects is conducted in an integrated framework.

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