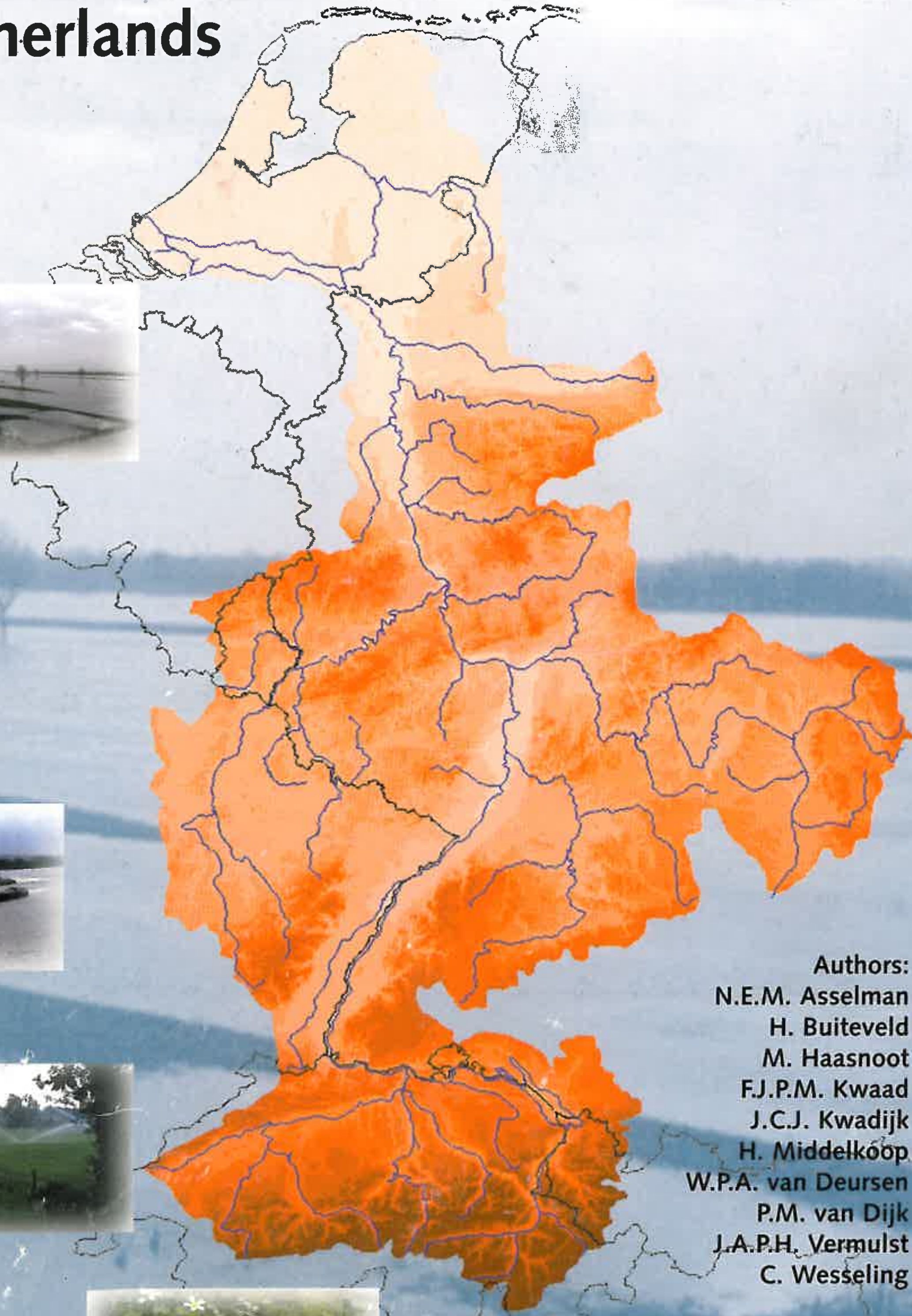
Exemplaar Margrit.

The impact of climate change on the river Rhine and the implications for water management in the Netherlands



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The impact of climate change on the river Rhine and the implications for water management in the Netherlands

Summary report of the NRP project 952210

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June 2000

RIZA report 2000.010
ICG-report 00/04
ISBN 9036953057
NRP project 952210
IRMA-SPONGE project 3/NL/1/164 / 99 15 183 0

NCR Netherlands Centre for River Studies

IRMA

Contribution to the CHR

CHR KHR

Preface

The present study has been carried out within the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP) - phase 2. The project was initiated by Dr. J.C.J. Kwadijk of Utrecht University and Ir. B.W.A.H. Parmet of RIZA, and it started in 1996. This report also contributes to the IRMA-SPONGE project nr. 3/NL/1/164 / 99 15 183 0.

The institutes that collaborated in the project are:

- Faculty of Geographical Sciences - Utrecht University,
- Institute of Inland Water management and Wastewater Treatment - RIZA,
- Landscape and Environmental Research Group - University of Amsterdam.

The following people and organisations are acknowledged for providing the project with data and feed-back on the results:

- CHR - For their co-operation in previous studies on the Rhine basin, which formed the basis of the present study, and for providing various types of data from the Rhine basin enabling the development of the RHINEFLOW-2 model
- GHR - C. Deelen, B. Luijendijk and P. van der Gaag and Ms. E. Snijders for their inspiring discussions and comments on our approach and modelling results.

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Contents

Summary

This report gives the extended summary of the NRP-project 'The impact of climate change on the river Rhine and the implications for water management in the Netherlands'. This study firstly addressed the effects of changes in climate and land use on the river regime, including runoff, sediment production, transport and deposition in the Rhine basin. For this purpose mathematical models based on a Geographical Information System have been developed. Secondly, the hydrological, morphological and ecological effects of soil subsidence, changes in the river regime and other climate related boundary conditions were investigated for inland water systems in the Rhine basin part of the Netherlands. This was done on the basis of a separation in three, connected, sub-systems, i.e. River Rhine branches, terrestrial areas and lake IJsselmeer, using existing models. For each of these subsystems the effects on the user functions were determined. Finally, by combining the expected impacts with possible measures for adaptation, the vulnerability of these functions to climate change was assessed. Also, mitigating measures aimed at preserving optimal water management were considered.

1 Introduction

In the Netherlands, located in the delta of the rivers Rhine, Meuse and Scheldt, of which large areas are lying below sea level and which is drained with an ingenious system of watercourses, canals, sluices and pumping stations, water is a major boundary condition for society. The River Rhine contributes about 65% of the annual inflow of fresh water into the country. The river also carries large amounts of sediment, as well as nutrients and pollutants from the upstream basin into the Netherlands. These supplies, however, all depend on the environmental conditions in the upstream Rhine basin. Along the western border of the country, a chain of dunes and dikes protects the lower parts from flooding by the sea. Because the subsoil of almost the entire country consists of loose sediment and peat, groundwater flow is an important component in the water balance of the land. With exception of some ice-pushed ridges and the southernmost parts, groundwater tables are shallow, and are artificially maintained at optimal levels by drainage canals, sluices and storage basins.

Rhine water is used in industry, in drinking water production, in agriculture and for water management in the polders. Furthermore, the river branches are part of the nation's transport infrastructure. At the same time, flood defence, nature, agriculture, recreation and mining all have to be accommodated on the relatively narrow strips of flood plain along the lower river branches. The IJsselmeer, the largest lake of the country, serves as a major freshwater basin for water management of the surrounding polders and is an important nature area. Safety, water availability and nature all have their demands on the lake levels, that to some measure can be artificially controlled. In the terrestrial areas there area many conflicts between agriculture demanding low water tables, and nature, that suffers from drought and nutrient influxes. Since so many activities and users have legitimate claims upon water in the Netherlands, a carefully considered and creative approach must be worked out by those responsible for water management.

Extreme weather events in recent years have raised the awareness that water management water plays a major role for our society. The floods seen in 1993 and 1995 demonstrated again the vulnerability of the low-lying Netherlands to flooding. In the summer of 1995 extremely low water levels occurred on the Rhine, which severely hampered inland navigation to Germany and Switzerland for weeks. The dry summers of 1976 and 1995 caused major drought damage to agriculture, while unprecedented heavy rainfall in October 1998 flooded large areas over many parts of the country. In this period, the water levels in the IJsselmeer, the largest inland lake of the country, rose dramatically, because the large flows of water entering from the surrounding polders and through one of the lower Rhine could not be discharged into the sea because of unfavourable wind.

Many of these events were regarded by some as the first signs of a climate change, although they may still fall within the range of the present day variability of discharge. Though there are inadequate data to determine whether consistent global changes in climate variability or weather extremes have occurred over the 20th century, the IPCC (1996) has concluded that a global warming trend has been occurring over the past century as a result of the increased emission of greenhouse gases into the atmosphere. Climate is expected to continue to change in the future, leading to worldwide changes in temperature and precipitation over the forthcoming decades. According to the IPCC-1996 'best estimate' scenario, the mean global surface temperature will increase relative to 1990 up to about 2 °C in the year 2100. On a global scale, precipitation may increase by several percents. Regional climate changes, however, can be different from the global average values.

Climate change will generally lead to a more vigorous hydrological cycle, influencing the components of the water balance of drainage basins in several ways. Changes in temperature, snow melt, precipitation amounts, patterns and intensities, and evapotranspiration will almost directly affect water availability and stream flow in rivers. Since climate changes will also affect the vegetation cover and soil erosion, they may also lead to changes in sediment production and sediment delivery to river systems. Changes in climate variables will directly affect agriculture and the needs for water supply and discharge during different parts of the year. Sea level rise, resulting from global warming, may affect safety standards of the coastal areas, and is expected to lead to an intensified intrusion of saline groundwater into the western part of the country. All these changes will both affect water supply (both in the sense of 'too much' and 'not enough') and water demand for the user functions of the Rhine and the other water systems in the Netherlands. Moreover, climate change may lead to an increase of the variability of hydrological variables. This is important, since water management strategies and the design of measures for controlling water distribution is usually based on extremes.

Considering the potential impacts of climate change, it is expected to put an extra pressure on the present-day competition between water users and between spatial claims for different functions that are geographically or functionally bound to the water systems. Although a great deal of uncertainty remains about the rate and magnitude of climate change, they may be so high, and their hydrological effects can be so crucial that they should be considered in future planning. For these reasons, sensitivity analyses should be carried out to investigate the potential effects of different climate change scenarios for the Rhine and the water systems in the Netherlands, and evaluate their potential impact on the user functions of these water systems.

1.1 Previous climate-impact studies in the Rhine basin and the Netherlands

Over the past decade several studies have been carried out that focused on climate change impacts on the Rhine basin. In the early eighties, a comprehensive study was undertaken in the Netherlands to assess the Impacts of Sea Level Rise on Society (ISOS) (Rijkswaterstaat, 1988). This study showed that the implications for the lower River Rhine branches and the large fresh water lake IJsselmeer are considerable, especially with respect to safety. However, the scenario changes for peak flows of the Rhine were not based on hydrological models, and alternative safety measures for dike rising methods were hardly considered. Research carried out in the framework of the International Commission for the Hydrology of the Rhine Basin (CHR) (Kwadijk, 1993; Parmet, 1994; Grabs et al., 1997) has shown that due to higher temperatures the river Rhine is expected to change from a combined rain-fed/snow-fed river towards a rain-fed river. Consequently, winter discharge will increase, with possible consequences for safety. The frequency and duration of low flows during summer increases, which together with higher temperatures will affect the river and floodplain ecosystems. Low flows will reduce water availability for economic functions such as inland navigation, agriculture, cooling water, public water supply and recreation. Furthermore, salt-water intrusion in the lower delta may increase, which affects agriculture.

Within the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP) (Zwerver et al., 1995), sub-theme 'Impact of climate change on regional hydrology', several research projects addressed effects of climate change on river discharge and the sediment budget of the river Rhine. Parmet et al. (1995) assessed the implications for the River Vecht (a small lowland tributary of the Rhine) in the context of the changes in the entire Rhine basin. Their results indicated that climate changes can have a significant influence on evapotranspiration, discharge and groundwater levels in summer, and leads to higher peak flows in winter (Parmet, 1994). Van der Drift (1995) investigated the effects of climate change on the susceptibility of loess areas in the Rhine basin, which they considered as the sources of the suspension load of the Rhine. Asselman (1995, 1997) provided first estimates of changes in sediment supply and sediment transport in the Rhine basin. She demonstrated that climate change will increase the production of sediment by rainfall erosion, and that the amount of fines transported by the Rhine will increase particular at high discharges. However, the estimates on future sediment supply are highly sensitive to the assumed changes in land use over the next decades, which was studied by Veeneklaas et al. (1994). Middelkoop (1995, 1997) and Asselman (1997) analysed the consequences of climate change for floodplain sedimentation along the lower Rhine branches in the Netherlands. Their results indicated that climate change would accelerate overbank sedimentation rates, which should be accounted for in floodplain landscape management plans.

For the preparation and underpinning of the Fourth National Policy Document on Water Management in the Netherlands, the Ministry of Transport, Public Works and Water Management has made a first assessment of the implications of soil subsidence, sea level rise and climate change for water management in the Netherlands (Werkgroep Klimaatverandering en Bodemdaling, 1997). Preliminary research results of the present NRP study were used for this assessment. The study evaluated different scenarios of climate change, which were in accordance with the estimates given by the Dutch National Meteorological Institute - KNMI (Können et al., 1997). The study also considered the consequences for the Rhine discharge, and put forward the potential consequences for safety, inland navigation, and water use for agriculture, controlling water levels in the polder areas and for industrial use. This study provided a first attempt of an integrated picture of the consequences for all freshwater systems in the Netherlands (including the lower river reaches, inland lakes and regional water systems). A policy of 'Making way for the river' and a no-regret strategy of planological reservations for water in combination with nature development were put forward.

These previous studies have provided potentially useful information to indicate the effects of climate change for river regimes and to assess the vulnerability of inland water systems and water management in the Netherlands to changes in climate related boundary conditions. However, in their present form they are incompatible in view of their differences in temporal and spatial scales. They also have a limited degree of integration, and considered adaptation strategies for user functions only to a limited extent.

1.2 Objectives

The study has two main objectives:

1. To assess the impact of climate change on the river Rhine and its tributaries, with respect to water discharge and suspended sediment supply. The assessment will be based on a range of consistent climate scenarios and taking into account expected autonomous developments in land use.
2. To assess the vulnerability of inland water systems for climate change, and the effects on water management in the Rhine basin part of the Netherlands, based on a range of consistent scenarios for changes in climate, river regime, and sea level rise, and also taking into account expected autonomous socio-economic developments.

1.3 General methods

The present study builds upon various studies that have addressed the impacts of climate change on the Rhine within the framework of the CHR and the NRP-phase 1. Existing databases and models have been combined and improved, and new modelling instruments were developed. The climate impact analysis of the present study involved two steps. In the first step, referred to as the river basin part, we determined the effects of climate change on the Rhine discharge and wash load supply from the Rhine basin to the Netherlands (figure 1.1). The output of the river basin part is the upstream boundary condition of the second major sub-project, referred to as the Netherlands' water management part. In the second step we analysed the vulnerability of inland water systems and water management in the Netherlands to changes in climate and in climate related boundary conditions such as river regimes and sea level. For this purpose, the physical changes in the boundary conditions for the user functions and water management were determined first. Subsequently, it was assessed to what extent these changes would affect the user functions. This was done by analysing whether there is sufficient excess 'slack' in the current water management system when compared to the expected changes in boundary conditions, and by evaluating possible opportunities for taking measures to prevent or counterbalance adverse or unfavourable effects on the long term.

1.3.1 Rhine basin

Sub-project 1a - Estimation of changes in the river Rhine discharge
Within the framework of NRP-1, the RHINEFLOW-1 model has been developed, simulating the water balance processes in the Rhine basin on a monthly time scale. To support this model, a geographical database has been constructed, containing maps of land use, soils, elevation, and hydrological and meteorological stations. Also, a meteorological database was constructed, containing monthly precipitation and temperature data for a large number of stations. In the present study the database has been refined to a 1 km x 1 km resolution, and the meteorological and hydrological data base were extended with 10-daily averages for temperature, precipitation and evaporation and river discharge. This data base served as a basis the development of a new RHINEFLOW-2 model, which simulates the water balance of the Rhine on a 1 km x 1 km resolution, using a time step of 10 days. After validation, the new RHINEFLOW-2 model was firstly used to simulate the discharge of the river Rhine under changed environmental conditions, such as climatic and land use changes, and the results were used as one of the inputs in the water management sub-project. Secondly, the model results and concept also formed the basis of subproject 1c that concerns the fluxes of sediment through the river Rhine.

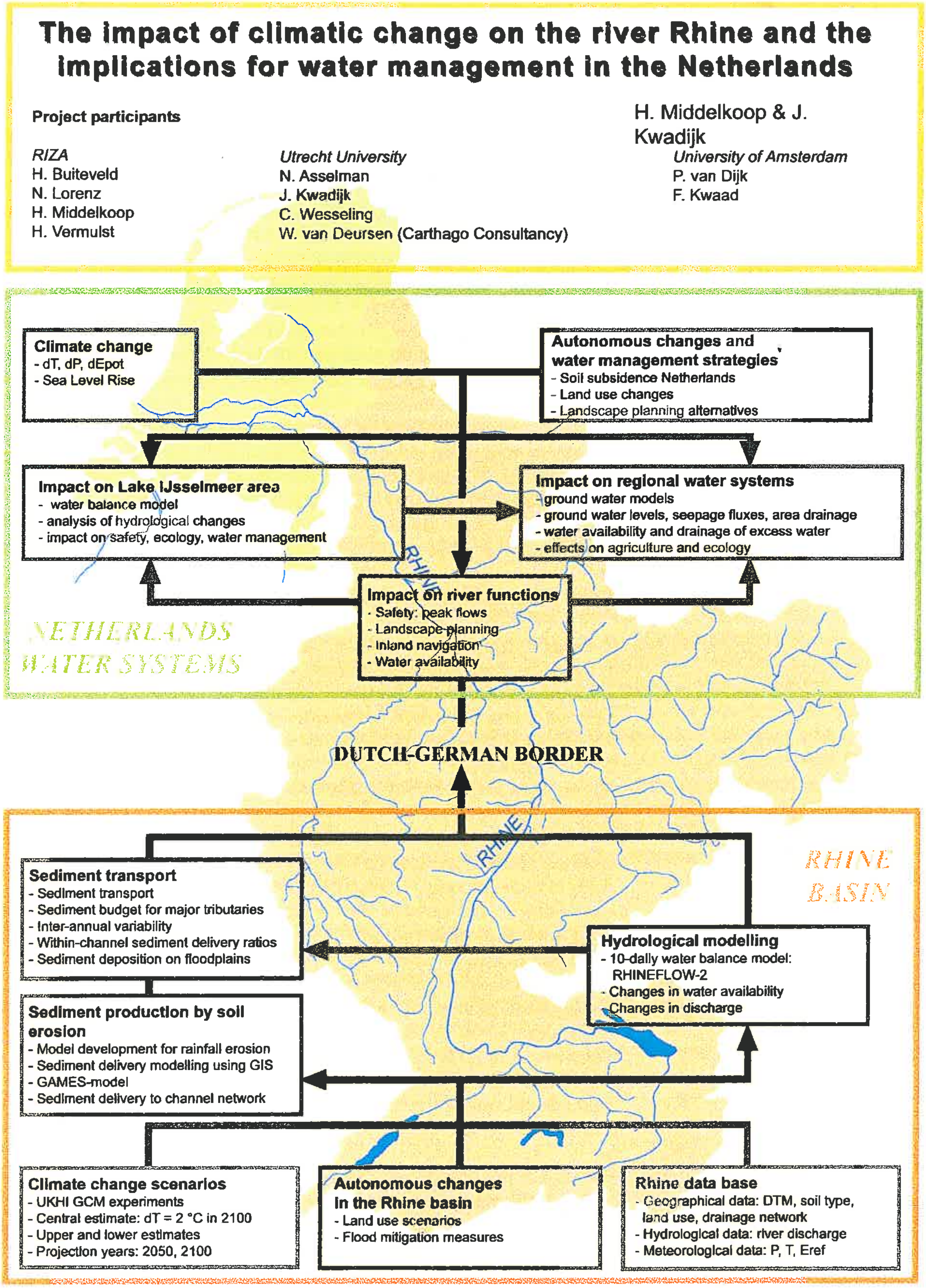

Figure 1.1 Outline of the project

Subproject 1b - Sediment supply

The sediment supply to the river Rhine was assessed using physiographic criteria. A set of USLE-type GIS modules was developed for the identification of the main source areas in the entire Rhine basin for the wash load in the Rhine. This part used the same database as the RHINEFLOW model. Subsequently, quantitative estimates of spatially distributed erosion of sediment by rainfall and subsequent delivery to the channel system were made at a basin-wide scale for various climate and land use change scenarios. The results formed the input for sub-project 1c that concerned the sediment transport through the river.

Subproject 1c - Sediment transport and fate in the Rhine basin

The result from the sub projects 1a and 1b as well as the results from the previous studies carried out in phase 1 of the NRP were combined to estimate the fluxes of sediment through the Rhine basin towards the Netherlands and the deposition within the lower Rhine delta. A suite of methods and models was evaluated to identify sediment delivery and sinks along the Rhine and deposition rates in the Rhine delta. Using these models the effects of environmental change on sediment delivery and fluxes were estimated. In combination with the water supply provided by subproject 1a, the results of this sub project form the upstream boundary conditions for a further analysis of the impact of environmental change on the water system in the Netherlands.

1.3.2 Water systems in the Netherlands - subproject 2

This part of the project involves the analysis of the impact of climate change on the water systems in the Netherlands, and assessment of the consequences for water management. For this study, the water systems in the Netherlands are subdivided into the following sub-systems:

1. the river Rhine distributaries with the lower Rhine-Meuse estuary
2. the IJsselmeer
3. regional or terrestrial areas.

Inputs for the analyses were the changes in river discharge and sediment supply from the Rhine basin resulting from the river basin part, sea level rise, and direct climate changes. Autonomous land use changes, and changes in water demand were considered as well. A major part of the analyses were carried out using existing models. These cover the hydrological, morphological and ecological aspects of inland water systems and allowed evaluating the effects on user functions as well. Most of these models have been developed for water management studies, such as the Policy Analyses for Water management in the Netherlands (PAWN), Aquatic Outlook, Water management studies for the IJsselmeer area (WIN-DSS), Landscape Planning of the Rhine (LPR-DSS) and for the Fourth National Policy Document on Water Management in the Netherlands. During the project, several of these models and databases have been improved, and a few new models have been added.

For each of the subsystems, the hydrological and morphological effects of different climate change scenarios were investigated first. Subsequently, the consequences for the user functions of the water systems were evaluated. In addition to model analyses, discussions and workshops were held with several stakeholders. In the final stage of the project, the effects on water management and possible mitigation measures were evaluated.

1.3.3 Scenarios

Climate change

Climate change scenarios were chosen such that they are consistent with the scenarios used in related studies in the Rhine basin and Netherlands. The climate scenarios for the Rhine basin were provided by the Climate Research Unit of the University of East Anglia (Hulme et al., 1994; Grabs et al., 1997). These scenarios are consistent with climate scenarios and established by KNMI for the Netherlands (Können & Fransen, 1996; Können et al., 1997). The scenarios were not considered as 'predictions' of future climate but they were considered a plausible basis for 'what-if' sensitivity analyses. In accordance with Können et al. (1997) a central estimate of climate change with a temperature rise equal to 2°C in the year 2100 was assumed, with a lower and upper estimates between +1°C and +4°C. Projection years in this study were 2050 and 2100.

Autonomous developments

Assessing the implications of future climate for current water management conditions may be regarded as a worst-case approach, because in practice, the water management system will have evolved and adapted to the changing climate conditions. Some developments affecting water management may occur independent from climate. These include population growth, land use changes, economic growth, changes in the legislative framework, and public and political attitudes to economy and environment (Arnell, 1998). Furthermore, soil subsidence of the lower parts of the Netherlands will proceed over the forthcoming decennia. These factors will not only influence water availability or water demand, but also determine the rate and type of adaptation to changing climate conditions. To account for such effects at least to some extent, two different base line scenarios were defined used as reference situations for the impact assessment. The first is the present situation, with present-day climate and actual conditions of the water system and current demands of the water users. The second reference considers autonomous (i.e. independent of climate) developments that may occur over the forthcoming decennia, projected to the year 2050. In this reference, climate remains unchanged.

1.4 Outline of the report

In accordance with the subdivision in a Rhine basin part and the sub-systems within the Netherlands, different researchers carried out different parts of the project. Results of individual components of the study were reported separately (table 1.1). This report gives the summary of all sub-projects per chapter, and integrates the overall results in chapter 14.

Table 1.1 Overview of researchers, sub-projects and reports of the project

Authors	Title of report and responsible institute
General	**RIZA - Utrecht University**
H. Middelkoop [1] H. Buiteveld J.A.P.H Vermulst [5]	Reference situations for assessment of climate change impact on the water systems of the Netherlands
H. Middelkoop [1] H. Buiteveld J.C.J. Kwadijk [2]	Climate change scenarios for hydrological impact assessment in the Rhine basin
C. Wesseling W.P.A. van Deursen [3]	Design and implementation of a database - http://rhine.geog.uu.nl
Sub-project 1a	**Utrecht University**
W.P.A. Van Deursen [3]	RHINEFLOW-2: Development, calibration and application
W.P.A. Van Deursen [3]	Impact of climate change on the river Rhine discharge regime - Scenario runs using RHINEFLOW-2
Sub-project 1b	**University of Amsterdam**
P.M. Van Dijk [4] F.J.P.M. Kwaad	The supply of sediment to the river Rhine drainage network - The impact of climate and land use change on soil erosion and sediment transport to stream channels
Sub-project 1c	**Utrecht University**
N.E.M. Asselman [2]	The impacts of changes in climate and land use on transport and deposition of fine suspended sediment in the river Rhine
Sub-project 2	**RIZA**
H. Middelkoop [1]	Estimating the impact of climate change on peak flows in the river Rhine
H. Middelkoop [1] H. Buiteveld	Implications of climate change for landscape planning alternatives for the river Rhine floodplains
H. Middelkoop [1] W.P.A. Van Deursen [3]	The impact of climate change on inland navigation on the river Rhine
H. Buiteveld N.N. Lorenz [2]	The impact of climate change on the IJsselmeer Area
M. Haasnoot J.A.P.H. Vermulst [5] H. Middelkoop [1]	Impacts of climate change and land subsidence on the water systems in the Netherlands - Terrestrial areas

Current institute:
(1) Utrecht University
(2) WLIDelft Hydraulics
(3) Carthago Consultancy - Rotterdam
(4) Université Louis Pasteur, Strasbourg - France
(5) IWACO - Maastricht

2 Study area

2.1 The Rhine basin

The Rhine basin (figure 2.1) covers an area of 185,000 square kilometres, some 25,000 square kilometres of it in the Netherlands. On the basis of its geographical and climatological characteristics, the Rhine basin can roughly be subdivided into three parts: the Alpine area upstream Basel, the German middle mountains between Basel and Köln, and the lowland area. The Alpine mountains comprise more than 16,000 km^2, with maximum elevations of more than 4000 m a.s.l., about 400 km^2 of which are covered with glaciers. The main tributaries in this area are the Aare, Reuss, Limmat and Thur rivers. The German middle mountains comprise the Vogesen and Black Mountains in the south, the Schwabische and Fränkische Alb along the eastern boundary of the basin, and the Rheinische Schiefergebirge in the central-northern area. Maximum elevations range from more than 1000 m a.s.l. in the south to around 600 m a.s.l. towards the north. The main tributaries within the middle part of the basin are the Neckar, Main, Mosel, Lahn and the Sieg. The lowland part comprises extensive sedimentary areas, including loess, (fluvio)glacial deposits, cover sands, and fluvial deposits of the lower river Rhine delta.

Climate

Climatic characteristics of the basin vary considerably for the three major parts of the basin. Within the Alpine area, large differences in precipitation occur, associated to both orographic and convective precipitation. Maximum annual precipitation in the mountains can be as much as 3000 mm, whilst in valleys at the lee side annual precipitation is only 600 mm. A substantial part of the precipitation is temporarily stored in a snow cover. Within the middle mountain area, climate parameters and their spatial variability are increasingly being determined by the site elevation. Whilst average temperatures decrease with elevation, high temperatures occur on sheltered valley slopes. Precipitation generally increases with elevation, with considerably larger annual precipitation at the west-exposed sides of mountain ranges, and low precipitation at the lee sides. In summer, convective precipitation is important within the lower areas. When accounting for altitude, average precipitation decreases from north to south. The climate of the lowland part is maritime in character, with a lower annual and daily amplitude of temperature than the upstream part of the basin. Annual average precipitation is about 750 mm.

Hydrological regime

The discharge of the river Rhine is mainly determined by the amount and timing of precipitation, snow storage and snow melt in the Alps, the evapotranspiration surplus during the summer period, and changes in the amount of groundwater and soil water storage. Figure 2.2 shows the present hydrograph of the river Rhine for different gauging stations along its course. The Alpine rivers are governed by a snow melt regime, with a pronounced maximum in summer. This maximum is generated by storage of precipitation in the snow cover in the winter, and its melting in spring and summer, amplified by summer rains. Retention of water in the Alpine border lakes has a smoothing effect on the Rhine discharge fluctuations. Downstream of Basel, the pluvial regime gradually starts to dominate the Rhine discharge. At the

Mosel confluence, the discharge maximum is moved to the winter season, maintaining however a considerable discharge in summer from the Alpine region. In dry periods, like the summer of 1976, the proportion of the discharge coming from the Alps can be as much as 95% (Kwadijk, 1993). The summer discharge minimum in the central and lowland areas is due to high evapotranspiration during the growing season exceeding the contribution of precipitation to the runoff, in spite of the precipitation maximum in the summer period. During the winter half-year, precipitation falls in the lower parts of the basin predominantly as rain, and eventual snowfall usually melts quickly. Going further downstream, the declining contribution of the tributaries to the mean annual runoff is mainly due to the regression of precipitation in the lower parts of the basin.

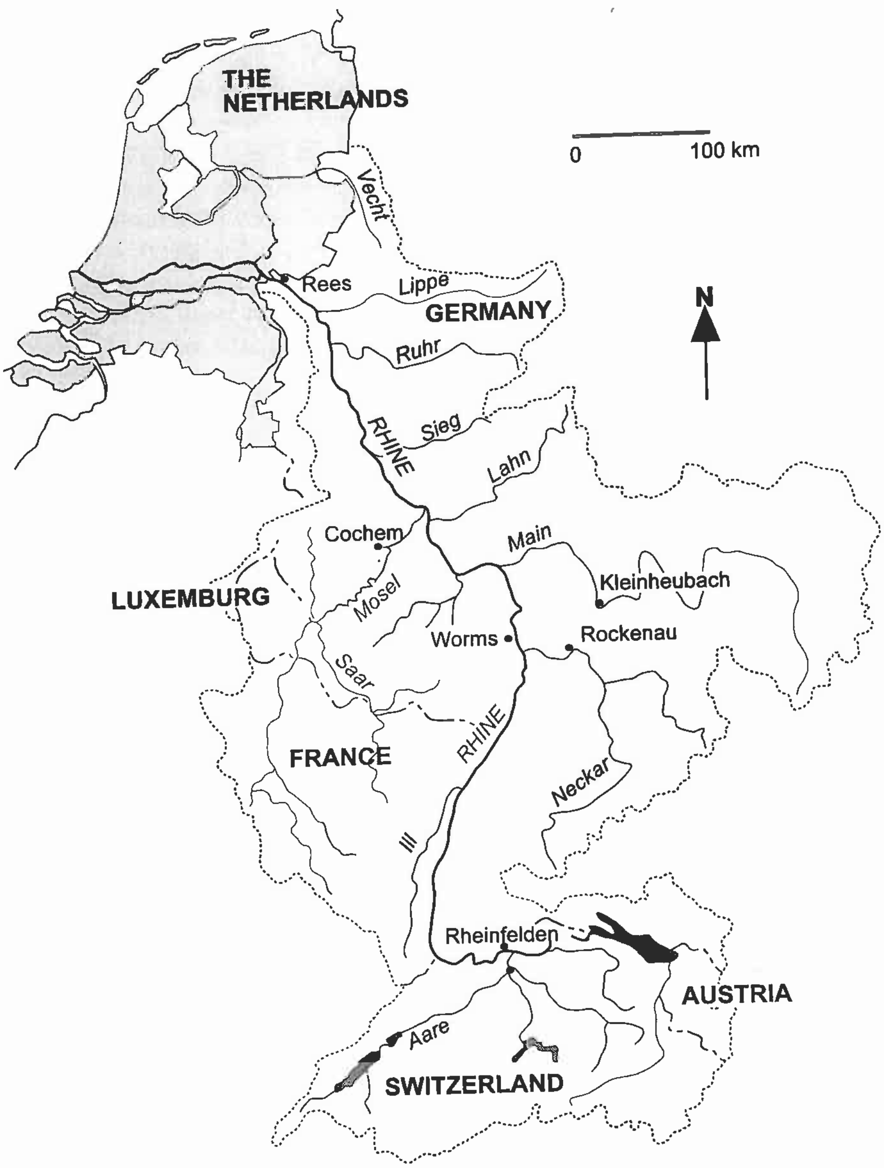

Figure 2.1 The Rhine basin

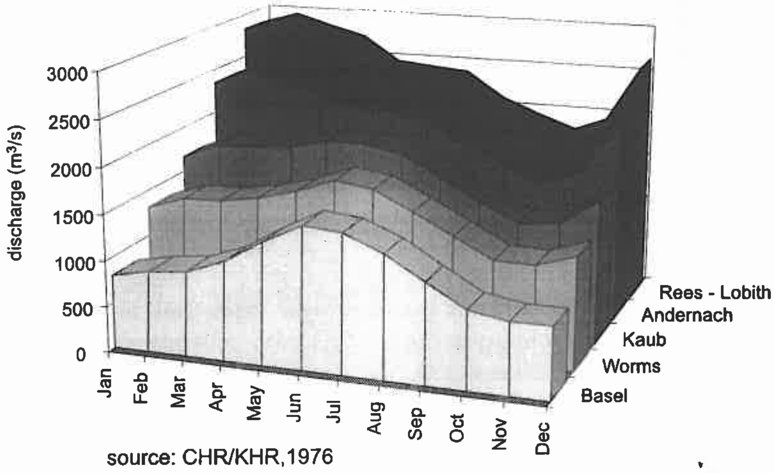

Figure 2.2 Hydrographs for different gauging stations along the Rhine

2.2 Water systems in the Netherlands

The lower river Rhine branches and their estuary, the IJsselmeer area and the regional water systems form a dense interconnected network of water systems (figure 2.3). River water enters through the rivers Rhine and Meuse and several smaller rivers such as the Overijsselse Vecht. Rhine water is distributed primarily over the large river Rhine distributaries and subsequently it is distributed over a great part of the country through a dense network of watercourses. Precipitation, river discharge and sea level determine water levels, discharge, and salt intrusion within the Rhine-Meuse estuary and the Lake IJsselmeer. Precipitation excess in the higher terrestrial areas in the eastern part of the Netherlands is drained through smaller watercourses into the rivers. To maintain the water levels in the low lying polder areas precipitation and seepage water is pumped from the polders into storage canals ('boezems'). In dry periods, water may be transferred into the opposite direction from the storage canals into the polders. Lake IJsselmeer plays a key role in the water management of the northern Netherlands.

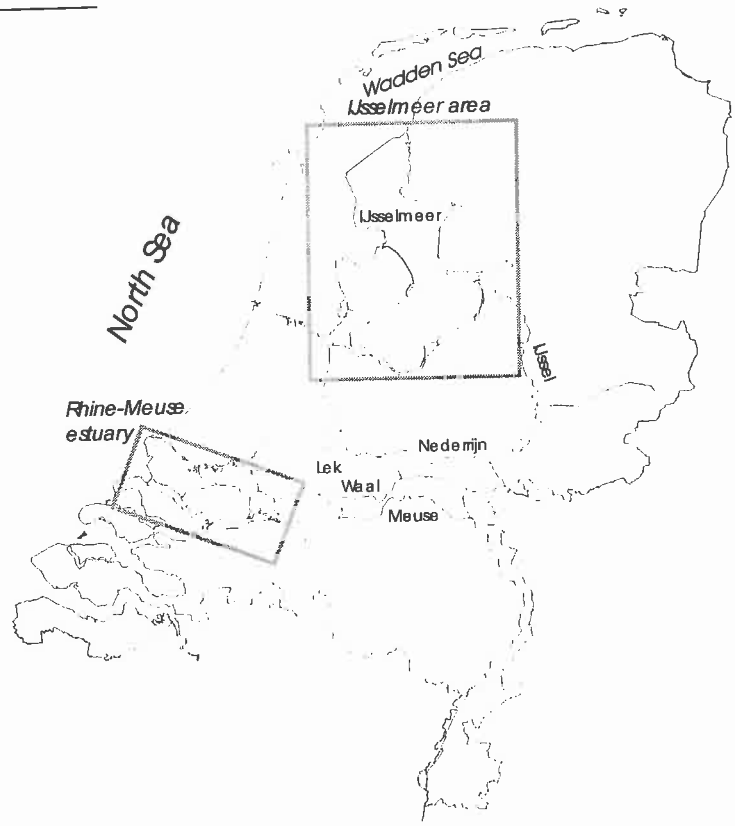

Figure 2.3 Water systems in the Netherlands. The regional water systems are not indicated separately

2.2.1 The lower River Rhine branches

The average discharge of the Rhine at the German-Dutch border is about 2,300 m^3/s. Each year, the Rhine carries about 400,000 m^3 of sand and gravel, and about 2,000,000 m^3 (which is 3.1 Mton) of fine suspended sediments into the Netherlands. In addition the river Rhine discharges pollutants, such as heavy metals, organic micropollutants and pesticides from the Rhine basin. In the Netherlands, the river Rhine divides in three distributaries. The largest is the river Waal, which carries about 2/3 of the total Rhine discharge, the other distributaries are the Nederrijn-Lek (about 2/9 of the Rhine discharge), and the IJssel (1/9 of the discharge). In addition to discharging water, sediments and other materials, the rivers fulfil important functions for the Netherlands:

Safety
The land along the lower Rhine branches is protected from river flooding by embankments. Safety standards for the areas bordering the Rhine in the Netherlands are based on a 'failure probability' of the primary embankments equal to 1/1250 per year. This design discharge is currently about 15,000 m^3/s; it is expected to be equal to 16,000 m^3/s in the next evaluation in the year 2001.

Water supply
Rhine water amounts about 60% of the annual input in the water balance of the Netherlands. It therefore is an important water supply for agriculture, industrial use, drinking water, and, in the lower parts of the Netherlands, for maintaining polder water levels and to prevent the intrusion of salt from the

North Sea. Rhine water is also used as cooling water for industry and power plants. Three weirs in the Lower river Rhine have been built controlling water flow, enabling to divert a sufficient amount of water into the Lake IJsselmeer during periods of low discharge. When the Rhine discharge is between 2300 m^3/s and 1400 m^3/s, the weirs ensure that the IJssel discharge does not become lower than 285 m^3/s. At lower Rhine discharge, the weirs are adjusted to preserve a minimum discharge equal to 25 m^3/s through the Nederrijn.

Inland navigation
The Rhine is the busiest river for navigation in Western Europe. In the Netherlands, the River Waal is the most important route. The number of ships passing Lobith amounts up to 170,000 a year. In 1990, the total transport over the Rhine along Lobith was 143 million tons. For the forthcoming decades a substantial growth of transport via inland navigation is foreseen.

Ecological functions
The river and its floodplains form an important interconnected network that provides ecological corridors for plants and animals. The Rhine Action Programme has resulted in a considerable improvement of water quality of the Rhine over the past decades. In the context of nature development projects, opportunities are being created for the return of plant and animal species that lived in and around the river in large numbers before mankind intervened.

2.2.2 Rhine-Meuse Estuary

The Rhine-Meuse Estuary forms the transition between the lower rivers Rhine and Meuse, and the marine area. This area is governed by both fluvial and marine influence, i.e. river discharge, tidal differences, and the transition from salt to fresh water. Since the estuary exhibits specific processes on morphology and ecology, the Rhine-Meuse estuary is considered as a separate sub-system. A more detailed description of this area is given in chapter 11.

2.2.3 Lake IJsselmeer area

The IJsselmeer area has an important function in the water management for the northern Netherlands. Excessive water from the northern part of the Netherlands is drained into the lake. During dry summer periods, water is supplied from the lake for agriculture. The water supply is also used to maintain the water level in the peat lands of the provinces of Noord-Holland and Utrecht. Many polders discharge their water into the lake during winter and take in water during summer for maintaining water levels and for controlling water quality. In Groningen, Friesland and Noord-Holland, water is taken from the IJsselmeer to flush the polder water, preventing the concentrations of chloride and phosphate becoming too high. A more detailed description of the area is given in chapter 12.

2.2.4 Regional Water systems

The regional water systems form a complex network of small rivers, drainage canals and storage canals. The function of these is to drain the higher parts of the land, which comprises the eastern and southern parts where Pleistocene sediments form the subsoil. This water is drained into the rivers and lake IJsselmeer. In the low-lying western and northern areas, excess water in the polders must be drained by pumping stations and drainage canals to storage reservoirs ('boezems'). During dry summer periods, fresh water must be conducted from the rivers and Lake IJsselmeer into the polder areas to control the polder water levels and to prevent the intrusion of saline groundwater.

3 Scenarios

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3.1 Climate change

The climate change scenarios used in this study have been derived from the IPCC IS92 greenhouse gas emission scenarios (IPCC, 1996), in combination with the scenarios given by the KNMI for the Netherlands. As a central estimate, a global temperature rise of about 2 °C is assumed for the projection year 2100. An uncertainty range around this central estimate of a factor 2 is assumed. This results in a lower estimate of 1 °C, a central estimate of 2 °C, and an upper estimate of 4 °C. The accordingly changes projected to the year 2050 are derived by linear interpolation.

3.1.1 Scenarios for the Rhine basin

Regional patterns in climate change for the Rhine basin were derived from the results of the MAGICC climate model in combination with the Hadley Centre's high resolution 11-layer atmospheric General Circulation Model (GCM), computed by the Climate Research Unit (CRU) of the University of East Anglia (Hulme et al., 1994). The scenario sets assume a business-as-usual development based on the standard IPCC emission scenario IS92a, assuming a central climate sensitivity of 2.5 degrees Celsius, and ignoring the effect of sulphate aerosols. An equilibrium experiment with this so-called UKHI GCM for the year 2100 indicated a temperature rise of about 4°C, which equals the upper estimate for temperature change in the Rhine basin. The UKHI2100 experiment was therefore be used as the upper estimate of climate change in the Rhine basin. Climate change estimates for the year 2050 were obtained by linear interpolation of the changes expected for 2100. This UKHI2050 estimate is used as the central estimate for climate change in the Rhine basin by the year 2100 and as the upper estimate for the year 2050. In a similar way the UKHI2020 experiment is used as the lower estimate for climate change in the Rhine basin by the year 2100. For the present study, the anomalies of mean monthly temperature and precipitation have been determined for each scenario. The were interpolated down to a grid resolution of 0.5° x 0.5° longitude/latitude. Expected regional temperature and precipitation changes according to the UKHI scenarios are summarised in table 3.1.

For the studies on soil erosion, not only changes in the *amount* of rainfall over the seasons are important, but also changes in rainfall *intensities*, particularly in the summer period. These, however, cannot be determined from the GCM results. In this study, the maximum 30-minute rainfall intensity (mm/h) is used to determine the rainfall erosivity. In summer, when small-scale convection is the main origin of erosive rainfall, maximum rainfall intensities are directly related to the daily mean surface air temperature (Klein Tank & Können, 1993).

A change in maximum precipitation is estimated using:

$$I_s = I_p * \exp(\tfrac{3}{2} * c * \Delta T)$$

in which

I_s = scenario maximum rainfall intensity (mm/h)
I_p = present maximum rainfall intensity (mm/h)
c = coefficient (0.073 °C^{-1})
ΔT = change in daily mean surface air temperature (°C)

Table 3.1 Changes in temperature and precipitation in different parts of the Rhine basin according to the UKHI experiment

		Alpine area			Central Germany			Lowland area		
		year	winter	summer	year	winter	summer	year	winter	summer
CEN2050,	dT(°C)	1.0	1.1	0.9	1.0	1.1	0.8	0.9	1.0	0.8
LOW2100	dP(%)	0.8	3.9	-2.3	2.4	5.7	-0.9	5.1	7.6	2.5
UP2050,	dT(°C)	2.2	2.3	2.0	2.1	2.4	1.9	1.9	2.2	1.7
CEN2100	dP(%)	1.8	8.6	-5.1	5.4	12.6	-1.9	11.3	16.9	5.6
UP2100	dT(°C)	4.2	4.5	3.9	4.1	4.5	3.6	3.8	4.3	3.2
	dP(%)	3.4	16.6	-9.8	10.3	24.3	-3.7	21.8	32.7	10.9

C-2050 = Central estimate for 2050
U-2050 = Upper estimate for 2050
L-2100 = Lower estimate for 2100
C-2100 = Central estimate for 2100
U-2100 = Upper estimate for 2100

voor Rijn stroomgebied → UKHI
KNMI → Nederland.

3.1.2 Scenarios for the Netherlands

Climate change scenarios for the Netherlands have been derived from the Dutch meteorological institute (KNMI) (Können & Fransen, 1996; Können et al., 1997). The KNMI indicated possible developments of future climate, and provided climate scenarios for hydrologic impact studies used for the Fourth National Policy Document on Water Management (NW4) (Werkgroep Klimaatverandering en Bodemdaling, 1997). As mentioned above, GCMs are not able to provide reliable information on changes in climate parameters on the scale of a small area such as the Netherlands. Therefore, the KNMI used alternative methods based on empirical relations between meteorological variables to derive climate scenarios for the Netherlands from large-scale climate models.

KNMI aannames:
- variabiliteit atmosferische circulatie + frequentie patronen niet veranderen

A key assumption of the KNMI methods is that the present variability of the atmospheric circulation patterns and the frequency distribution of circulation patterns around NW Europe do not change in response to the greenhouse warming. Under this precondition, it is a plausible estimate that the (seasonal) temperature rise in the Netherlands will not be much different from the global mean temperature rise. In addition, the method also assumes that the empirical relations among the meteorological variables remain preserved in a changing climate. Therefore, the KNMI explicitly mentions that their scenarios for the Netherlands are conditional statements that heavily rely on these key assumptions. The changes indicated are compared to the situation in the year 1990. An overview of the changes of the meteorological variables that are relevant for the present study is given in table 3.2.

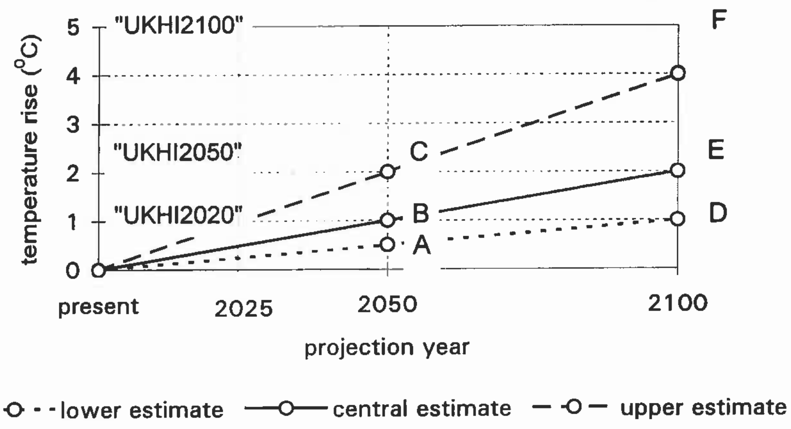


Figure 3.1 Climate change scenarios used in this study: lower, central and upper estimates for different projection years, and relation with the UKHI GCM experiment.
A = lower estimate for 2050
B = central estimate for 2050
C = upper estimate for 2050
D = lower estimate for 2100, same climate change as B
E = central estimate for 2100, same climate change as C
F = upper estimate for 2100

Changes in relative sea level, which are relevant for the IJsselmeer area and coastal regions, comprise two components:

1. an autonomous rise with a component that cannot be explained by model simulations over the past century. This component includes the effect of tectonic subsidence and model errors, and is about 10 cm per century;
2. an accelerated rise due to global warming. According to the central estimate this would result in a relative sea level rise for the Netherlands of about 60 cm by the year 2100. The scenario estimates for changes in sea level for all projections are summarised in table 3.3.

Table 3.2 Changes in Temperature and Precipitation in the Netherlands according to the KNMI scenarios (Können et al., 1997)

	2050 - central estimate (B) 2100 - lower estimate (D)	2050 - upper estimate (C) 2100 - central estimate (E)	2100 - upper estimate (F)
Annual avg. temperature	+ 1 °C	+ 2 °C	+ 4 °C
Number of days with ice thicker than 12 cm	- 34%	- 60%	- 85%
Total annual precipitation	+ 3%	+ 6%	+ 12%
Total summer precipitation	+ 1%	+ 2%	+ 4%
Total winter precipitation	+ 6%	+12%	+ 25%
Intensity of convective rainstorms in summer	+ 10%	+ 20%	+ 40%
Prolonged winter precipitation	+ 10%	+ 20%	+ 40%
10-daily cumulative winter precipitation, De Bilt	+ 10%	+ 20%	+ 40%
present recurrence time			
1 yr (= 61 mm)	0.7 yr	0.5 yr	0.3 yr
10 yr (= 97 mm)	6 yr	4 yr	2 yr
100 yr (= 135 mm)	47 yr	25 yr	9 yr

Table 3.3 Summary of increased sea level rise (in cm) due to global warming for different scenarios of climate change (RIKZ, 1995; Können et al., 1997), including the 'unexplained' component (10 cm/100 yr)

Projection	unexplained component (cm)	Lower estimate + unexplained component (cm)	Central estimate + unexplained component (cm)	Upper estimate + unexplained component (cm)
2050	5	10	25	45
2100	10	20	60	110

3.1.3 Conclusion

The climate scenarios presented here may be not considered as predictions of a future climate, but must be regarded as a plausible basis for a sensitivity analysis. By combining lower, central and upper estimate of changes and different projection years a time-climate change space was established that formed the basis for this assessment study (figure 3.1).

3.2 Autonomous developments

Climate change impact assessment involves a comparison between a situation with changed climate conditions and a situation without climate changes. The situation without climate change is referred to as a baseline or reference scenario. It represents the conditions to which climate change scenarios are applied, and it forms the basis on which the different climate scenarios are projected. For the Climate Impact Assessment to be carried out in this NRP project, two reference scenarios have been defined. These are (1) REF1995, which is the present situation, and (2) REF2050, which represents the reference situation for the year 2050.

REF2050 includes various 'autonomous' developments on water management, landscaping, land use and economy and ecological rehabilitation. These trends have been derived from previous studies, such as the socio-economic scenarios given by the CPB (1993), the Aquatic Outlook scenarios (Projectgroep Watersysteemverkenningen, 1996), and policy trends indicated in policy documents such as the Fourth National Policy Document on Water Management (NW4; VROM/V&W, 1997). For the present study, it is assumed that the most plausible autonomous developments within REF2050 are those which reflect an extrapolation of the current policy on water management, rural planning, economy and ecology. In many aspects, REF2050 reflects the trends in the CURRENT POLICY scenario of the Aquatic Outlook and the CPB-scenario EUROPEAN RENAISSANCE.

A second type of non-climate induced development is land subsidence. A major part of the Netherlands, especially the polder and river areas, are subjected to land subsidence. The three major causes of land subsidence in the Netherlands are (1) oxidation and settlement of Holocene deposits, especially peat soils, due to intensified drainage conditions; (2) mining activities, especially those of gas and (3) tectonic movements. Figure 3.2 shows the spatial variation in soil subsidence projected to the year ~~2100~~. 2050

The REF2050 used for the present study is a rather hypothetical situation, and it should be regarded as a projection of current trends and policy lines to the year 2050. It provides a basis for analysing the effects of climate change in a situation where the trends and changes that are presently foreseen will, at least for a part, have taken place. In this way, it can be used to analyse whether or to what extent these trends are in accordance with the expected climate-induced changes for the water systems. The extrapolations of autonomous developments according to the current policy, which are used as the REF2050 situation, are summarised in table 3.4. Various policy variants according the current policy are summarised in table 3.5.

Table 3.4 Autonomous developments according to the current policy, used in REF2050

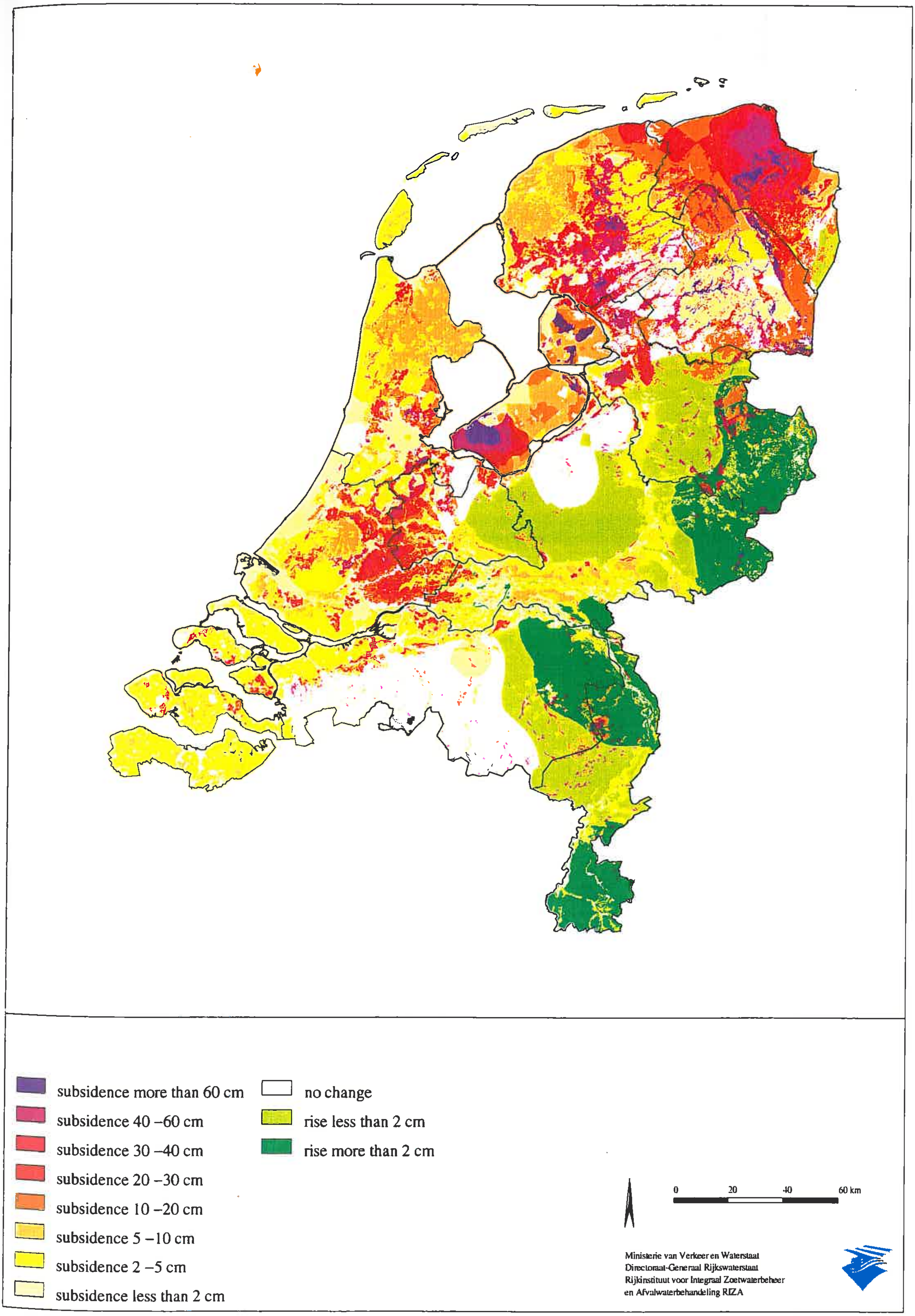
Sub-system	Variable	Reference / variants	Characteristics
Rivers	flood water retention capacity	IKSR strategies	water conservation and retention in Rhine Basin, estimated reduction design discharge 0 - 500 m^3/s
	floodplain landscaping	LPR-variants	three alternatives: (1) current land use, (2) nature development, (3) nature-culture preservation
	transport by inland navigation	EUROPEAN RENAISSANCE (CPB)	increase of transport from 217 Mton to 386 Mton
IJsselmeer	sea level rise	autonomous trend	10 cm rise in 2050 (land subsidence included) tidal difference increased by 5 cm
	target levels of the lake	current lake levels	-0.4 m NAP in winter, -0.2 m NAP in summer
	nature development	current policy	increase shallow shores and swamps 2050 hectares
	sluice management	SYSTEM POLICY (Aquatic Outlook)	sluice management allowing better fish migration
	changes in water releases and demands	current policy	Wieringermeer releases directly to Wadden Sea; increasing water demands for industry, agriculture and domestic use
Rhine-Meuse Estuary	sea level rise	autonomous trend	10 cm rise in 2050 (land subsidence included) tidal difference increased by 5 cm
	management of the Haringvliet sluices	BROKEN TIDE (HV2min) (MER-Haringvliet)	minor increase tidal wave from 0.2 m to 0.4 m; slight upstream shift of salt intrusion
Terrestrial areas	land subsidence	autonomous trend	land subsidence 0 - 60 cm due to settlement and oxidation, mining activities and tectonic movements
	sea level rise	autonomous trend	7 cm rise of average sea level in 2050 (land subsidence excluded)
	land use changes	EUROPEAN RENAISSANCE (CPB)	decrease agricultural land use by 2300 km^2; increase nature 1500 km^2 and urban area 700 km^2
X	reduction of desiccation	CURRENT POLICY (Aquatic Outlook)	water management measures and manipulating groundwater extractions aimed at 30 % reduction

klopt niet

Table 3.5 Summary of alternative visions on water systems

Sub-system	Variable	Reference / variants	Characteristics
Rivers	flood water retention capacity	IKSR strategies	water conservation and retention in Rhine Basin, estimated reduction design discharge 0 - 1000 m^3/s
	floodplain landscaping	LPR-extension	adapted discharge distribution over Rhine distributaries
	transport by inland navigation	1. GLOBAL SHIFT 2. BALANCED GROWTH (CPB)	1. increase of transport to 282 Mton; 2. increase of transport to 399 Mton;
IJsselmeer	target levels of the lake, sluice management changes in discharges and water demands	RADICAL CHANGE POLICY (Aquatic Outlook) RADICAL CHANGE POLICY (Aquatic Outlook)	0 m NAP in winter, -0.4 m NAP in summer model results Terrestrial areas
Rhine-Meuse Estuary	management of the Haringvliet sluices	1. TAMED TIDE 2. STORM SURGE BARRIER (MER-Haringvliet)	1. tidal difference = 60 to 70 cm, reduced salt intrusion 2. sluices only closed during storm
Terrestrial areas	land use changes	BALANCED GROWTH (CPB)	decrease agriculture of 3800 km^2; increase nature 2500 km^2, urban area 700 km^2
	reduction of desiccation	RADICAL CHANGE POLICY (Aquatic Outlook)	water management measures, manipulating groundwater extractions and alternative measures aimed at 100 % reduction in 2050

Next page
Figure 3.2 Soil subsidence in the Netherlands projected to the year ~~2100~~ 2050


subsidence more than 60 cm
subsidence 40 –60 cm
subsidence 30 –40 cm
subsidence 20 –30 cm
subsidence 10 –20 cm
subsidence 5 –10 cm
subsidence 2 –5 cm
subsidence less than 2 cm
no change
rise less than 2 cm
rise more than 2 cm
0
20
40
60 km
Ministerie van Verkeer en Waterstaat
Directoraat-Generaal Rijkswaterstaat
Rijksinstituut voor Integraal Zoetwaterbeheer
en Afvalwaterbehandeling RIZA

4 Design and implementation of a database

Cees Wesseling
Willem P.A. van Deursen

4.1 General aspects

For the previous NRP-Rhine study a database for the river Rhine with a spatial resolution of 3 by 3 kilometre and a temporal resolution of 1 month was established. As part of this NRP-project this core database has been extended. The extensions include the scope of the database, the spatial resolution of the database and the temporal resolution of the database. Based on this core database, a set of input data for Rhineflow 2.0 has been established. The database has been made accessible to other parties through a WWW-application, which also presents a summary and the major results of the entire project.

The main purposes of the database are:

- ensure access of all project-participants to the most recent and accurate data
- ensure access of all project-participants to model runs, their associated input data sets and the results
- provide a platform for external parties to take notice of the project, provide demos and descriptions of the work executed in the framework of the project.

Within the NRP-II project new geo-referenced geographical data for the River Rhine has been collected. The scope of this database has been extended, it now includes primary data that can be used for hydrologic, sediment supply and transport modelling purposes. The interface of the database consists of HTML pages that embeds 1) all documentation, 2) all relations between data through hyperlinks between the pages and 3) download buttons.

4.2 Contents of the database

The database contains the following datasets:

- General purpose data
  - soil maps
  - land use maps
  - DEM
  - drainage pattern
  - catchment delineation.
- Data for the Rhineflow 1.0 and Rhineflow 2.0 model (at a 1x1 km grid scale)
  - model parameters, such as
    - cropf: crop factor (rhineflow)
    - rainzone: rainzone (rhineflow)
    - whold: water holding capacity (rhineflow)
  - initial values, such as
    - apwlinit: apwlinit (rhineflow)
    - gwinit: initial groundwater level (rhineflow)
  - geographical data
  - model results for several climate change scenarios
- Data related to erosion and sediment loads
  - daily discharge and sediment concentration measurements

  - parent material of dominant soil types
  - parent material of secondary soil types
- Hydrological and meteorological data sets
  - daily precipitation
  - daily reference evapotranspiration
  - daily minimum, maximum and mean temperature
- Climate Scenario files (temperature change and precipitation change)
  - ESCAPE Climate Change files (2050,2100)
  - UKHI scenario from UK Hadley Centre (2020,2050,2100)
  - XCCC scenario from Canadian Meteorological Office (2020,2050,2100)

The spatial data are stored as a raster GIS with a spatial resolution of approximately 1 square kilometer. All datasets can thus be used by the Rhineflow model and related models.

4.3 Metadata and datasources

More than 50 different datasets are collected, categorized and documented in the core database. All data sets in the core database are accompanied by a set of metadata, describing source and other relevant information. The database also contains the associations and relations within the datasets. For derived datasets, the database contains the rules for acquiring these derived datasets. This feature enables automatic updating of derived information. If, for example, better elevation data becomes available all information that is derived from the elevation, such as drainage networks, is automatically updated in the database. The automatic update of data provided an efficient mechanism to proceed with data analysis while waiting for the final or missing data, since results can be re-computed when better data is available.

A large part of the data used in the current study has been provided by the CHR/KHR. As in previous Rhine basin studies (Grabs et al., 1997) the CHR plays an important role as a facilitator in the exchange of data and modelling results. The GIS-data have been collected by the GIS-group of CHR from a number of providers and have been stored in ARC-INFO format. These vector-based data are converted into the grid maps for the core database.

4.4 WWW presentation NRP Project

For information about the project to external parties a web site is established at http://rhine.geog.uu.nl. The site contains a general introduction, information on the sub-projects and an example of results of the project. The example of results of the project shows changes in snow cover duration in the Alps under a climate change scenario. The WWW presentation shows a sequence of 20 maps that illustrates that the snow-covered area in the Alpine part of the catchment will reduce drastically in the next century under the selected climate scenario.

5 Impact of climate change on the discharge regime of the Rhine - scenario runs using RHINEFLOW-2

Willem P.A. van Deursen

5.1 Model development and calibration

This chapter describes the calibration and scenario runs with the RHINEFLOW-2 model. RHINEFLOW-2 is an extended version of the RHINEFLOW-1 model (Kwadijk, 1993), a GIS based water balance model for the Rhine catchment. RHINEFLOW-2 is developed within the framework of the Dutch NRP-2 project. RHINEFLOW-2 extends the database of RHINEFLOW-1 to a 1x1 km2 grid (RHINEFLOW-1: 3x3 km2), and uses a time step of 10 days (RHINEFLOW-1: 1 month). Furthermore, RHINEFLOW-2 uses a more detailed description of the snow storage-snowmelt processes, and changed the formulation of the evapotranspiration process.

5.1 Introduction
For studying the impacts of climate change in the Rhine basin the RHINEFLOW-1 model was developed [Kwadijk, 1993; Van Deursen and Kwadijk, 1993]. This RHINEFLOW-1 model is a regional scale GIS based model which evaluates the impacts of climate change in the various compartments of the water balance. This model has been developed as a conceptual water balance model on a 3x3 km2 grid and a monthly time step. The results of the application of the model with the climate change scenarios indicate that the hydrologic regime of the Rhine will shift from a combined rain-snow fed regime to a rain-fed regime.

The RHINEFLOW-1 model uses standard meteorological input variables of temperature and precipitation, and geographical data on topography, land use, soil type and groundwater flow characteristics. These parameters are stored in a raster GIS with a spatial resolution of 3x3 km2. Simulations of evapo-transpiration are performed using the concepts of Thornthwaite-Mather. Snow-accumulation and snowmelt are simulated using a temperature-index method. Runoff is simulated by adding a baseflow component as output from a linear 'groundwater-reservoir' to the excess surface water generated by the Thornthwaite-Mather soil compartment simulation. In addition to time series for river discharges, the model produces maps showing temporal and spatial distribution of a number of hydrological variables, such as potential and actual evapotranspiration, snowfall percentage, snow cover duration etcetera.

RHINEFLOW-2 continues along the lines defined in the RHINEFLOW-1 project. Whereas RHINEFLOW-1 used a temporal resolution of 1 month, this timestep is considered to be too long for a detailed study of the impacts of Climate Change on the functions of the river and the formulation of water management strategies to deal with these problems. For a proper analysis of the problem, a shorter timestep is considered essential.

The aims of RHINEFLOW-2 is to give detailed information about the hydrological response of the Rhine catchment to Climate Change scenarios. In this context, climate change scenarios are defined as timeseries of change in precipitation and temperature in the Rhine catchment, which will be superimposed on present precipitation and temperature timeseries. RHINEFLOW-2 is developed to simulate impact of changes in the water balance components. It thus can be used to simulate impact of changes in precipitation, which are the input for the water balance. Changes in evapotranspiration are equally straightforward simulated, since these terms are the loss-terms for the water balance. Impact of changes in land use and changes in water management practices are less straightforward. As long as these changes result in significant changes in evapotranspiration rates, RHINEFLOW is capable of simulating them. However, many water management changes and land use changes do not cause so much in changed evapotranspiration rates, but their impact is more on retaining water and timing of flows. These changes have to be very large to have distinct effects on the RHINEFLOW-2 results.

5.2 Concepts of the RHINEFLOW-2 model

RHINEFLOW simulates the water balance of the Rhine catchment as a series of storages of reservoirs. RHINEFLOW recognises 3 compartments as storages or reservoirs: the snow compartment, the soil compartment and the deep groundwater compartment. Each of these compartments is implemented as a GIS-layer, thus allowing for simulating spatial characteristics of the compartments. For each of the timesteps in a model run, these reservoirs are updated, representing the temporal behaviour of these storages.

5.2.1 Data base

The following dataset is available for the RHINEFLOW-2 model:

- temperature data
  - stations with min, max and mean 10 day station temperature
- precipitation data
  - stations with 10 daily areal (subbasin-) precipitation
- evaporation data
  - stations with reference station evapotranspiration data (10 day estimates)
- runoff data
  - stations with 10 day discharge data

Although the spatial resolution of the model is 1x1 km^2, and thus individual cells can be evaluated at this level, the calibration and validation of the total Rhine basin do not assure a correct estimate for individual cells. Although the scale at which data is stored in the GIS is 1x1 km^2 and the results can be made available on the same scale one should be extremely careful to use this scale as an evaluation scale of the model. It is impossible to calibrate and validate the model for this spatial resolution, and thus local assessments can not be made based on a regional model. However, the model will be calibrated and validated for sub-catchments, and the results should be applicable to this scale. For the level of subcatchments of tributaries of the Rhine the model will produce reliable results.

5.2.2 Simulating processes in the Snow compartment

Within the snow compartment the following processes are simulated:

- Snowfall
- Snowmelt
- SnowStorage.

There are various solid forms of precipitation that, before being drained from the catchment, remain on top of the surface for some time. For this study, snow is the most important. In most alpine regions, snowmelt runoff is responsible for the annual maximum instantaneous discharge and most of the annual flow. Due to their steep, variable topography, alpine catchments are characterized by a large degree of heterogeneity in the important properties controlling snow accumulation, snowmelt and meltwater runoff.

Snow accumulates on the surface, storing a certain amount of water, and releases its contents when melting. This might occur in one specific event or as a series of melting and refreezing of water. Within catchments the size of the Rhine, there may be several locations at which melting occurs, while simultaneously snowfall and accumulation occurs at other locations.

The impacts of climatic change are critical to regions with seasonal snowcover, because increased frequency of rain-on-snow events, changes in precipitation volumes, changes in timing of accumulation and ablation seasons, and changes in location of the snow line all affect snowmelt runoff occurrence and the availability of water.

The process of snowfall, -accumulation and snowmelt is governed by the energy available, mainly provided by the radiative net heat flux. Both conceptual and physical approaches have been employed in snowmelt-runoff modelling. Conceptual models propose a mathematical relationship between snowmelt and measured quantities; thus melt can be calculated without treating in detail all the physical processes and parameters that affect snowmelt.

For RHINEFLOW-2 a snow module is developed with the following characteristics.

- Simulation of snowfall and snowmelt based on both minimum and maximum temperature for each timestep. Snowfall will be triggered by minimum temperature, and the fraction of precipitation falling as snow equals the fraction of the temperature-interval between minimum and maximum temperature that is below this 'snowfall trigger temperature'.
- Simulation of snowmelt based on both minimum and maximum temperature for each timestep. Snowmelt is triggered by the maximum temperature. Snowmelt is decreased for the fraction of the temperature interval that is below this 'snowmelt trigger temperature'.
- Some slow flow mechanism (representing glaciers and snow moving downhill). This mechanism is necessary because the descriptions of the snow module otherwise allows a snowcover to build up for ever, thus creating a very large 'sink of water' from which water will never again become available.

5.2.3 Soil compartment

Within the soil compartment the following processes are simulated:

- Actual and potential evapotranspiration
- Partition of excess water in a slowflow and a quickflow component
- Budget of the soil moisture

Inputfluxes for this compartment are the SnowMelt and Rainfall terms calculated in the snow compartment module. OutputFluxes for this module are the Quickflow and Slowflow terms.

The RHINEFLOW-1 model simulated this soil compartment and its major terms with a Thornthwaite-Mather formulation of evapotranspiration and soil moisture budget. This approach is limited for its applications in Climate Change studies. The main reasons for this limited applicability are:

- The Thornthwaite-Mather approach uses an empirical model, with as main independent variable temperature. The use of this type of formulae for Climate Change studies results in an over-estimation of potential evapotranspiration.
- The Thornthwaite-Mather formulae are developed for the use in the United States. Applying these formulae in other areas is with considerable potential problems.

Better estimates of potential evapotranspiration in the Rhine catchment under current climate conditions are available from the meteorological institutes in the catchment. The task for RHINEFLOW-2 is to estimate changes in evapotranspiration due to changes in climate, the task is not to estimate evapotranspiration under present day conditions. RHINEFLOW-2 uses an approach in which the available reference evapotranspiration data for the current situation is used. For climate change scenarios, a mathematical relation between temperature change and reference evapotranspiration change is used. This relation for the Dutch situation is derived by Brandsma (1995), and can be established for other areas using Penman (for a very detailed estimation) or Blaney-Criddle (for a good and more robust estimate). This relation becomes external to the RHINEFLOW-2 model, and is implemented as a tabular relation between temperature change and evapotranspiration change.

5.3 Model calibration

For calibration and validation of the RHINEFLOW-2 model, we used the time series for discharge stations at Lobith, Kaub and Maxau. The period from January 1961 to July 1966 was used for calibration. The calibrated model was validated for the period from January 1961 to December 1990.

The three criteria used for calibration are the Nash-Sutcliff coefficient of efficiency, the correlation between measured and simulated mean monthly discharge and the correlation between the frequency distribution of the measured and simulated discharge. Although RHINEFLOW-1 was calibrated using only the Nash-Sutcliff coefficient, the additional criteria are considered important because the Nash-Sutcliff coefficient is predominantly sensitive to timing of peaks and less sensitive for a strucural under- or overestimation of peakflows or low flows. . A model that is capable of describing the average regime of the river may very well result in a high coefficient. The relatively sparse occurrences of high and low discharge situations might be simulated weakly, without disturbing the coefficient too much. Considering the application of the model, impacts of climate change on the discharge, we chose to pay some more attention to these extreme situations, and thus introducing additional calibration parameters.

Despite its simplicity, the model is quite accurate. Annual discharge is estimated by the model within 5 percent of the observed value. The model efficiency for the Lobith gauging station is 0.55, which is lower than the efficiency of RHINEFLOW-1. Higher efficiencies are possible, but this results in unacceptable low correlations for the mean monthly discharge values and in unacceptable low correlations between the frequency distributions of actual and simulated discharge. Simulated and measured runoff for the three stations is given in figure 5.1.

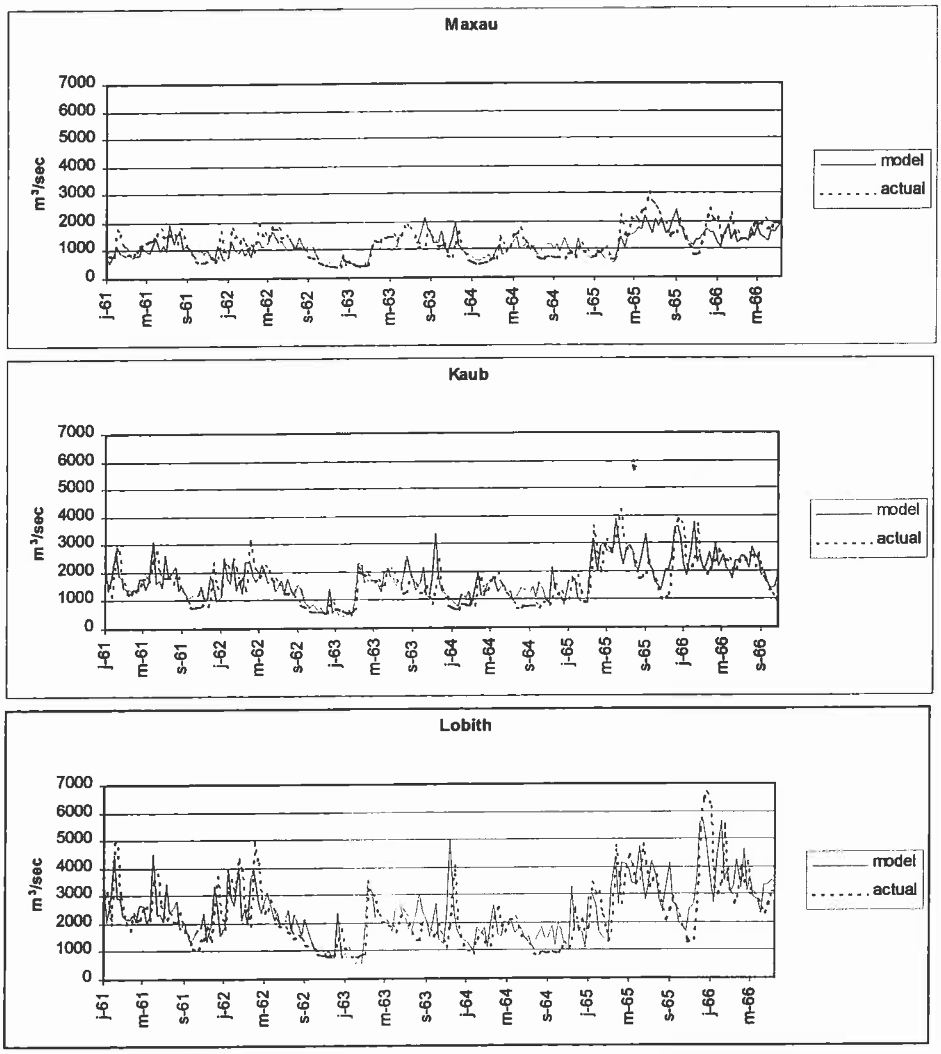


Figure 5.1 Simulated and measured discharge selected stations

5.4 Model results for changed climate conditions

To analyse the impacts of climate change on the discharge regime of the Rhine two scenarios were used. The used scenarios suggest that the climate will be changing more and more towards the end of the century. The scenarios show an increasing precipitation in winter and spring and a decreasing precipitation in (late) summer and autumn.

In the entire basin temperature is expected to increase and local and regional differences in this increase are expected to be small. Precipitation changes are expected to show a spatial variation over the basin. Larger increases may occur during winter in the north-western and eastern parts of the basin while somewhat larger decreases are expected during summer in the southern Alpine parts.

The selected scenarios show an increase in winter runoff, and a decrease in summer runoff. This is caused by three mechanisms:

- increased winter precipitation,
- increased winter temperatures resulting in a decrease of snow storage and snow melt
- increased temperatures resulting in increased summer evapotranspiration

The combined effects will result in a shift to a predominantly rain-fed river, implying increased average late winter and spring discharges and lower summer and autumn discharges. These results are in agreement with the earlier, less detailed results with the RHINEFLOW-1 model.

Figure 5.2 shows the simulated discharge at the Lobith gauging station according to the UKHI scenario. The results in figures 5.2 and 5.3 indicate that the climate conditions as simulated by the UKHI scenario will lead to increased maximum flows in winter at the Lobith gauging station and decreased flows in summer. Furthermore, these results suggest that the peak flows now occurring in March will occur earlier and be higher. The present day average peak is estimated to be 3080 m^3/s, occurring in decade 9, while in 2100 this peak is estimated to be 4330 m^3/s, occurring in decade 3. This can be explained by analysing the snow storage in the basin: increased winter temperatures will decrease snow storage and increase winter discharge, combined with the effects of increased winter precipitation. Again, this yields the conclusion that the Rhine will change from a combined rainfed – snowfed river to a predominantly rainfed river.

Using the defined scenarios, the low flows simulated by this model do not show a very pronounced change. The model parameters controlling this low flow behaviour do not change under the scenario conditions, and since precipitation changes are defined as a percentage of current precipitation nor does the length of the drought periods. More research is recommended into low flow situations and their relations with climate change.

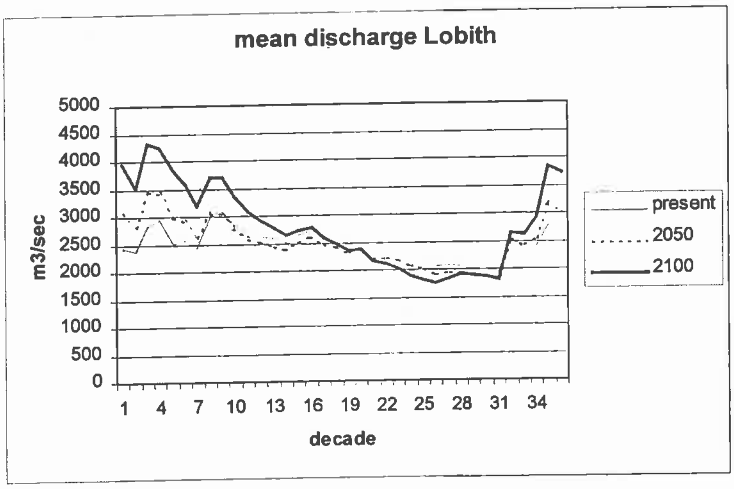
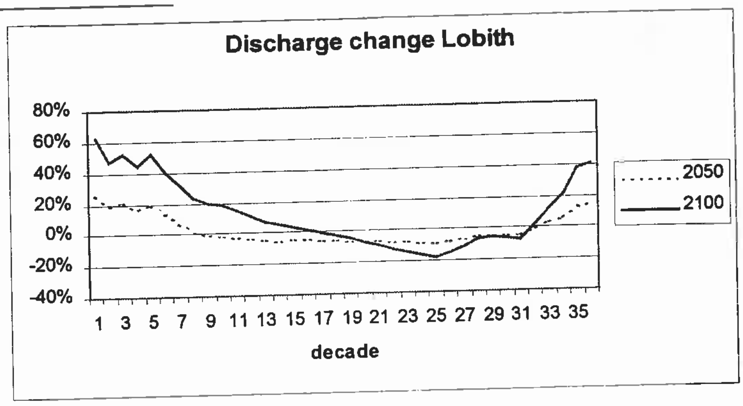
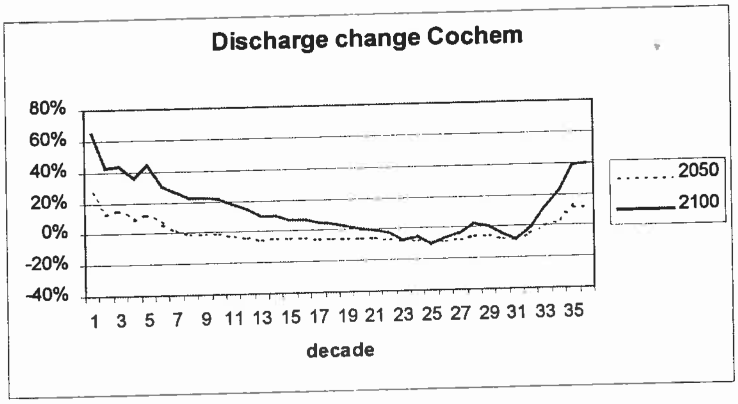


Figure 5.2 Scenario runoff regime at Lobith





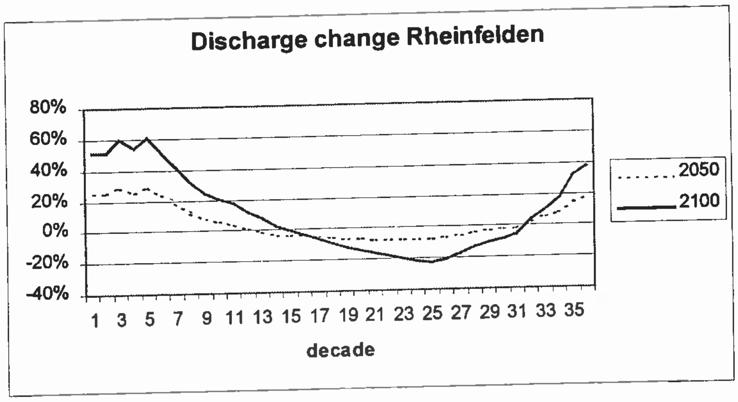


Figure 5.3 Runoff changes (in %) for selected stations

6 The supply of sediment to the river Rhine drainage network

Paul M. Van Dijk
Frans .J.P.M. Kwaad

6.1 Introduction

In the framework of a climate change project, research has been carried out addressing the impact of environmental changes on the hydrologic regime and the sediment budget of the river Rhine. The research described in summary in this section deals with estimations of soil erosion and sediment supply to the drainage network of the river Rhine. The study has resulted in a distributed model, which was subsequently used to assess the impact of climate and land use change on the sediment supply system.

6.2 The model

The sediment supply model is called RECODES: the **R**hine model for evaluating effects of **E**nvironmental **C**hange **O**n **D**elivery of **E**roded soil to **S**treams. The approach and model development included the following steps:

- The creation of a basic spatial GIS-database. It contains vital information with respect to soil erosion and sediment supply: a) relief/morphology, b) soil features (i.e. texture), c) land use and d) the drainage network.
- The identification of the sediment delivery processes. This led to the development of a conceptual model for sediment supply to the drainage network.
- The selection of a simple mathematical model (GAMES) (Dickinson & Rudra, 1990) and further extention of this model such that it agreed with a) our conceptual model, b) the data availability, because by necessity only existing data were used, c) our requirements with respect to spatial and temporal detail in output, and d) the requirement of being suitable for climate/land use scenario calculations (it must contain parameters which are sensitive to changes in rainfall/temperature).
- The creation of a database containing all model input parameters. Many of them were derived from the basic data set mentioned earlier, others were based on literature data. Attention is paid to problems that are specific to the large size of the studied basin and the spatial resolution of the available data set. Some morphologic input parameters were validated through comparison with values derived from detailed topographic maps, scale 1:25.000.

In RECODES, concepts of the GAMES-model are used as a basis. According to GAMES, the amount of mobilised sediment that actually reaches the stream network depends on the proximity of the sediment source to the stream, the occurrence of overland flow and on the character of the terrain along the route towards the channel (including surface roughness and slope angle).

The sediment supply model enables us to identify areas that actively deliver sediment to the Rhine drainage system, assuming soil erosion on hillslopes to be the primary sediment source. Model output is sediment production and sediment delivery on a long-term monthly average basis, using long-term monthly average meteorological input data. The supply model makes use of some Rhineflow routines to model the soil water balance.

6.3 Model sensitivity

A sensitivity analysis of RECODES showed that the model output is most sensitive to the variables slope angle (*s*), precipitation amount and erosivity (*P+R*), curve numbers (*CN2*) and temperature (*T*), and to the USLE-factors (Figure 6.1). The slope angle is a variable, which is possibly prone to systematic errors in our database and thus may cause systematic under-, or overestimations of the sediment supply. Especially if the slope angles are overestimated, the overestimation of sediment supply is high. With respect to absolute estimates of sediment supply rates, the variable 'slope angle' is a major source of uncertainty.

Precipitation amounts, rainfall erosivity and temperatures are supposed to be rather accurate model inputs. Although the model is sensitive to these variables, they are not considered an important source of uncertainty. The curve numbers, which depend on soil features, soil moisture and land use, are strongly affecting the modelled sediment supply. The validity of the *CN*-method in RECODES strongly depends on the quality of the modelled soil moisture. For soil erosion and sediment supply, the Rhineflow routines have sufficient quality to show the major spatial patterns of soil moisture regimes. The spatial resolution is restricted to the resolution of the basic soil map as several relevant variables used in these routines are derived from this map. Finally, the sensitivity analysis showed that the model output is only moderately sensitive to the variations in the transport distance (*l*). However, the uncertainty in the estimation of this input parameter is supposed to be rather high. Therefore, the uncertainty in the model output due to error in *l* may still be significant.

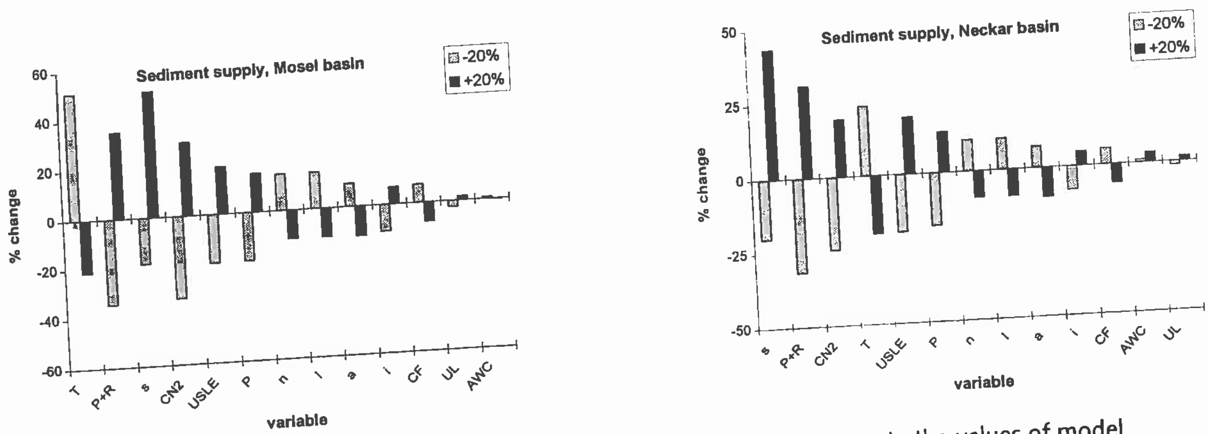


Figure 6.1 Sensitivity of modelled sediment supply to a 20 % increase and decrease in the values of model parameters. (To temperature a change of 3° is applied, as a percent change for temperature is undefined). (a) the Neckar basin, and (b) the Mosel basin

6.4 Modelling results for present-day conditions

With RECODES, present-day erosion and sediment supply was estimated. The total sediment production for the entire basin is estimated to be 23 Mt/year, while total supply to the drainage network amounts approximately 11.7 Mt/year (≈ 50% of the production). Thus according to these calculations, about half of all hillslope sediment production is delivered to stream channels.

The model identifies the following primary sediment source areas (figure 6.2): a) the Swiss middle land, including large parts of the Aare basin, b) the southern Rhine valley along its steep edges, especially between Basel and Strasbourg, including parts of the Black Forest, Alsace and Vosges, c) the central and downstream part of the Neckar and the Main basin with agricultural land use and highly erodible soils, d) between Mainz and Landau, west of the Rhine, e) the downstream part of the Mosel basin and f) the loess area between the rivers Lippe and the Ruhr.

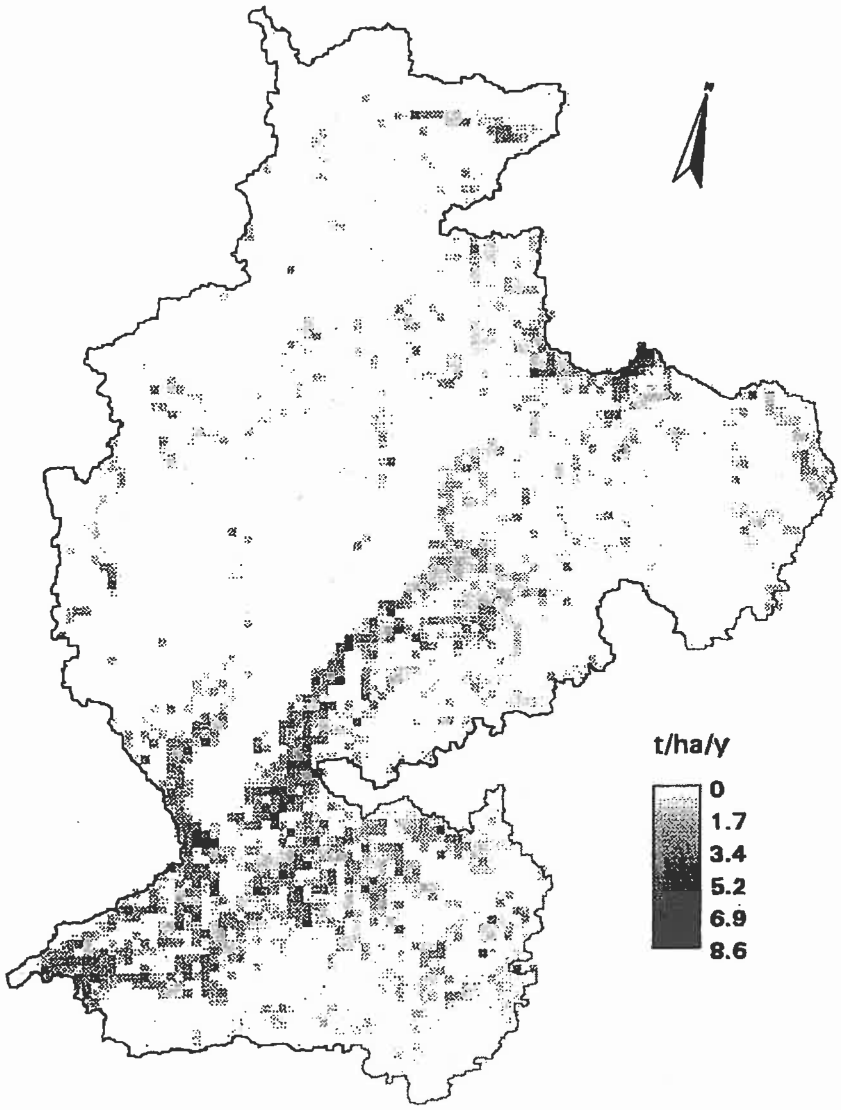


Figure 6.2 Modelled annual sediment supply to the Rhine basin drainage network under present-day climate and land use conditions.

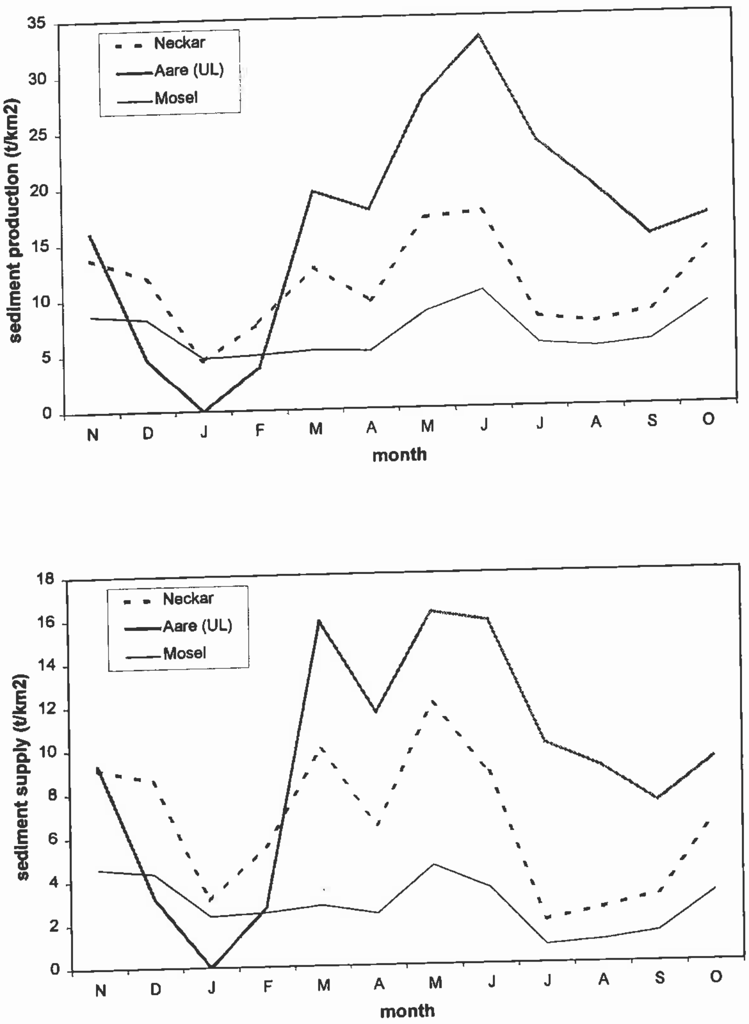


Figure 6.3 The simulated temporal patterns of erosion (a) and sediment supply (b) for three subbasins within the Rhine basin.

6.5 Model evaluation

The modelling results for present-day conditions are evaluated by means of

- an uncertainty analysis
- a categorical validation of computed erosion rates using literature data
- a comparison of the sediment supply figures with measured sediment yields for six sampling stations in the Rhine basin.

Uncertainty analysis
The uncertainty analysis of the RECODES model shows the model output should not be evaluated at the scale of the individual raster cell; results should be evaluated for larger areas, by aggregating raster cells. A main problem in the uncertainty assessment is the fact that little is known about the quality of the basic maps. Still, it is clear that large part of the uncertainty in the model predictions is due to errors in morphometric parameters as these were derived from low spatial resolution data, which do not reflect the situation on the hillslope scale. These errors affect the absolute sediment supply figures. The morphometric parameters, however, are relative insensitive to climate change.

Therefore, the estimated *relative* change in sediment supply due to climate change, as calculated by the model, is expected to have less uncertainty.

Validation of computed erosion rates

It is shown that the erosion module of RECODES produces meaningful average erosion rates, which correspond well with aggregated field data on erosion rates (figure 6.4). However, the model seems to overestimate erosion for some individual categories of arable land use, in particular for row crops. On the basis of this categorical validation, the net overestimation of the erosion in the Rhine basin by RECODES is estimated to be 36 % at maximum. This error is based on the assumption that the measured erosion rates obtained under different soil and land use conditions, as found in the literature, are representative for these conditions.

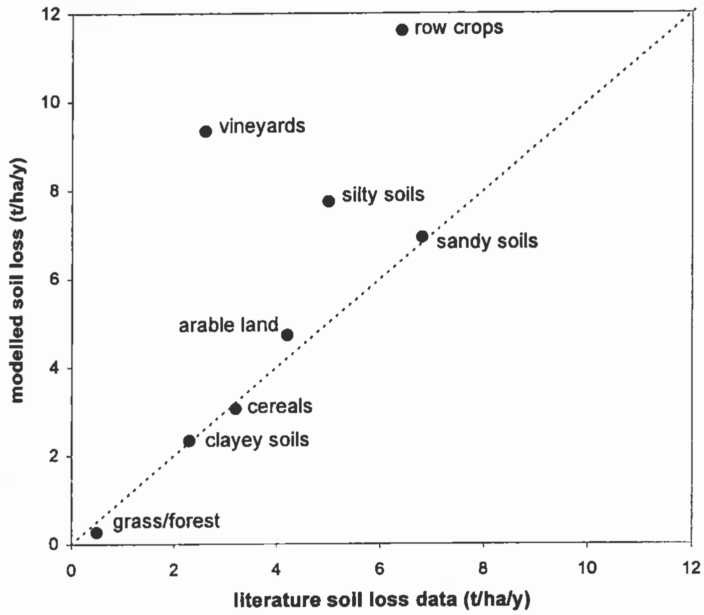


Figure 6.4 A comparison of the modelled erosion rates and erosion rates taken from the literature for several land use and soil texture categories (the categories have overlaps)

Sediment supply versus the river's sediment yield

In spite of the uncertainties regarding the absolute levels of erosion rates and sediment delivery ratios for the hillslope, the modelled sediment supply appears to have reasonable levels. Still, large differences exist between the modelled amount of sediment supplied to the drainage network in the Rhine basin and the sediment yields as measured in the major rivers. These differences apply to both the amount of sediment and to the temporal patterns. It is shown that alluvial processes (like temporal and semi-permanent storage of sediment) indeed play an important role in the basin and may be responsible for these differences. However, at present, it is not possible to say which part of the differences can be explained by these alluvial processes and which part is caused by modelling errors. The results of this study indicate that suspended sediment is stored in the alluvial system in the summer and removed during the runoff season.

6.6 Results of the scenario study

In figure 6.5, the results of the scenario calculations are summarised. For the Rhine basin downstream of the Alps, a decrease of sediment supply is predicted, at least for the lower (-16 %) and central estimates (-11 %) of climate change. For the upper estimate of climate change an increase of 8 % is calculated.

For the Alps, the model results indicate that erosion and sediment supply will increase significantly. This effect of environmental change is likely to occur. However, the application of the sediment supply model to steep mountainous areas is rather dangerous and the results, thus, are probably unreliable. The sediment supplied in the Alps is trapped in the many large lakes at the foot of the Alps in Switzerland. This sediment is not available for transport to the Dutch waters. Therefore, the modelling results for the Alps are left out of consideration in the final figures that describe the effects of environmental change on erosion and sediment supply.

For the Rhine basin downstream of the Alps, a decrease of sediment supply is predicted, at least for the lower (-16 %) and central estimates (-11 %) of climate change. For the upper estimate of climate change an increase of 8 % is calculated.

An evaluation of RECODES has shown that large part of the uncertainty in the model predictions is due to errors in morphometric parameters, as these were derived from low spatial resolution data, which do not reflect the situation on the hillslope scale. The errors affect the absolute sediment supply figures. These morphometric parameters, however, are relative insensitive to climate change. Therefore, the estimated *relative* change in sediment supply due to climate change, as calculated by the model, is expected to have less uncertainty. Therefore, the results of the scenario calculations are presented as per cent changes, relative to the figures for 1990.

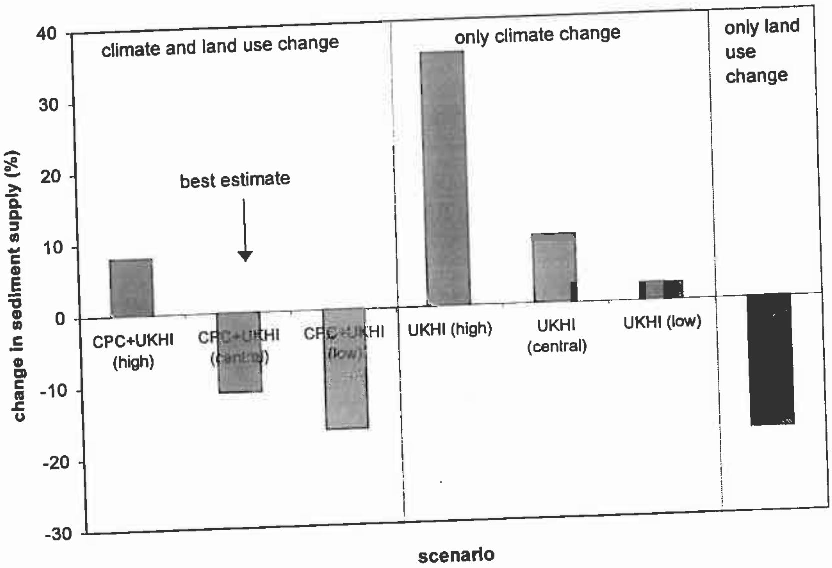


Figure 6.5 The impact of climate and land use changes on the supply of sediment to the river Rhine drainage network, according to the scenario calculations. The results apply to the entire Rhine basin excluding the areas upstream of the large lakes at the foot of the Alps

6.7 Conclusions

Environmental change is expected to affect erosion and sediment supply processes. On the basis of this scenario study for the year 2050, in which we used the UKHI 2050 climate scenario (central estimate) and the CPC land use scenario, the following conclusions can be drawn for the basin area downstream of the Alps:

- In large part of the Rhine basin, the projected land use changes cause sediment supply to decrease while the projected climate changes have the opposite effect.
- Locally, annual erosion rates are expected to increase, mainly because the erosivity of rainfall and runoff increases.
- Notwithstanding all that, regional erosion rates will hardly change or decrease only slightly in many subbasins, because the area of land use types which are susceptible to erosion is expected to decrease.
- Processes related to snowfall, snow cover and snowmelt will become much less important in many French and German subbasins. This affects the temporal pattern of erosion and sediment supply.
- The sediment delivery to the streams becomes harder due to lower soil moisture levels, especially in the season of high erosivity. Therefore, in general, the sediment supply rates will decrease.

According to this scenario study, the amount of sediment that is mobilised by soil erosion and supplied to stream channels by overland flow, and which is potentially available for transport to the Dutch waters, is likely to decrease slightly (with about 11%). This conclusion holds for the central ('best') estimate of climate change as employed in this report (UKHI 2050) and the CPC land use scenario. The supply of sediment will increase if land use does not change (i.e. remains similar to the land use in 1990) or if the climate changes more than projected in the UKHI 2050 scenario.

7 The impacts of changes in climate and land use on transport and deposition of fine suspended sediment in the River Rhine

Nathalie E.M. Asselman

7.1 Introduction

7.1.1 Background

In many lowland rivers a major part of the sediments is transported in suspension. In the German lowland rivers, such as the Rhine, suspended sediment makes up about 85% of the total solid sediment transport (Hinrich, 1974). In the past, little research was carried out on transport and deposition of fine suspended sediment. Recently, however, interest in fine suspended sediment dynamics has increased. This is mainly the result of the increasing awareness of the role of fine suspended sediment in the transportation of pollutants and the significance of floodplains and reservoirs in storing contaminated sediments. Besides this aspect of environmental protection, fine sediments often settle in reservoirs that are constructed for protection against flooding, for recreation, or for drinking water supply. Sedimentation limits the lifespan of these reservoirs. Also, some of the fine suspended sediment load is deposited in navigation channels in the delta area of the river or in river locks (e.g. Van Dreumel, 1995; Kern, 1997). These deposits impede shipping, which implies extensive and expensive dredging. Finally, sedimentation also occurs on the embanked floodplains (e.g. Asselman & Middelkoop, 1995). Depending on the amount and quality of the deposited sediment, this may reduce possibilities for river restoration. Moreover, continuing sedimentation will reduce the discharge capacity of the high water bed, i.e. the area between the main channel and the major river dikes. This will increase the risk for flooding.

7.1.2 Problem definition and objectives

One of the most important consequences of climatic change will be alterations in major climate variables, such as temperature, precipitation, and evapotranspiration. This in turn will lead to changes in land use type, vegetation, and hydrological regimes, which will affect erosion on hilllslopes. As transport and deposition of fine suspended sediment (wash load) depend on the availability of loose material, changes in soil erosion may subsequently affect sediment transport and floodplain sedimentation rates. There have been very few studies into the implications of global warming on erosion and sediment transport.

The objective of this part of the study is to assess the impact of climate change on suspended sediment transport in the river Rhine, and on the deposition of suspended sediment on the embanked floodplains in the Netherlands. The following objectives are defined:

- to quantify sediment loads in different parts of the river Rhine and its tributaries,

- to analyse and quantify the processes that govern sediment transport in the Rhine and that determine the delivery of sediment through the channel downstream,
- to model transport and temporary deposition of suspended sediment in the Rhine as a function of river discharge and sediment supply,
- to determine rates and patterns of contemporary floodplain sedimentation, and
- to estimate possible changes in sediment transport, and floodplain sedimentation in response to changes in climate and land use conditions.

7.2 Suspended sediment in large rivers: a review

The suspended sediment dynamics of large rivers often are difficult to determine because of the complex relationship between sediment transport rates and water discharge. This complexity is caused by the fact that the amount of fine suspended sediment (wash load) transported by the river depends on the availability of loose material, as well as on the capability of the river to transport this material. Variations in the timing of sediment supply from different source areas or tributaries may further complicate this relationship.When a model is developed to estimate fine suspended sediment transport in large river systems, the following phases should be taken into account:

1) Soil erosion or production of suspended sediment.
2) Transport of the eroded material into the river.
3) Sediment transport and deposition in the main channel. A small part of the sediment that is supplied to the river contributes immediately to the sediment load at the catchment outlet. A large part of the sediment is deposited on the channel bed. Behind weirs, current velocities are too low to transport sediment under low flow conditions. Under high flow conditions, however, sediment is eroded again. The presence of weirs thus results in temporary storage of sediment over periods of a few months up to several years. Long-term storage of sediment (varying from decades to centuries or more) occurs in large lakes or reservoirs, and at the floodplains.

The sediment transport regime at the outlet of large drainage basins is determined by the amount of sediment supplied to the drainage network, by the efficiency of the drainage network to transport this material, and by the timing of sediment supply from the different tributaries. The ratio between the amount of material eroded from the hill slopes and the material transported out of the catchment is referred to as the sediment delivery ratio (SDR). The SDR of a drainage basin consists of two parts. The first part comprises the delivery of sediment from the hill slope into the nearest channel. The percentage of the material that reaches the stream is called the hill slope sediment delivery ratio (HSDR). The second part of the SDR of a drainage basin is determined by the percentage of the sediment that is supplied to the stream and that reaches the catchment outlet. This is called the channel sediment delivery ratio (CSDR).

7.3 Study area and available data

The study area covers the entire Rhine basin. Erosion and sediment transport are studied in the Rhine upstream of the German-Dutch border, whereas floodplain sedimentation is studied for the main Rhine distributary in the Netherlands.

Sediment transport data used in this study were provided by the Bundesanstalt für Gewässerkunde in Germany. Additional data were found in the literature. Data were provided by the BfG for the measurement locations indicated in figure 7.1. The data records for the different gauging stations vary in length, but at most locations measurements have been carried out since the early or mid seventies (table 7.1). Drainage areas upstream of the measurement locations are derived from CHR/KHR (1976, 1989).

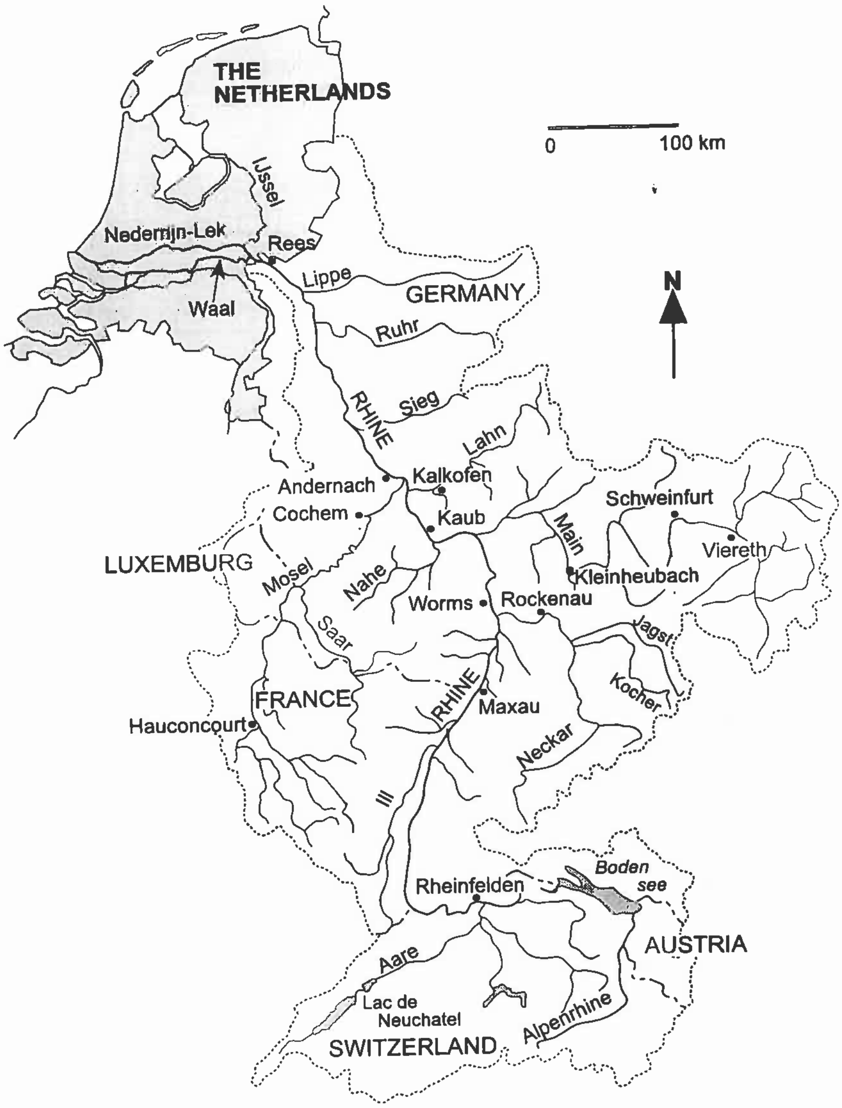


Figure 7.1 Measurement locations in the Rhine basin

Table 7.1 Suspended sediment load (Qs) of the river Rhine and its main tributaries

Station	Period	Upstream area (km²)	Q_s (10^6 t/yr)
Rheinfelden (Rhine)	'77-'90	34550	1.12
Maxau (Rhine)	'75-'91	50200	1.16
Worms/Nierstein (Rhine)	'84-'90	68827	1.40
Kaub/Bacharach (Rhine)	'71-'90	103730	2.16
Andernach/Weissent. (Rhine)	'75-'90	139800	3.48
Rees/Emmerich (Rhine)	'75-'91	159300	3.14
Rockenau (Neckar)	'72-'90	12676	0.47
Schweinfurt/Viereth (Main)	'73-'89	12715	0.10
Kleinheubach (Main)	'87-'90	21505	0.34
Kalkofen (Lahn)	'71-'90	5305	0.08
Hauconcourt (Mosel)	'75-'80	9400	0.24
Cochem/Brodenbach (Mosel)	'82-'90	27088	0.88

7.4 Concept of a suite of linked models to simulate sediment transport in the Rhine

7.4.1 River discharge

The impact of climate change on the monthly discharge frequency distribution of the river Rhine was studied by Kwadijk (1993) with the Rhineflow-1 model.The monthly discharge estimates were converted to daily discharge estimates using a statistical relation between monthly average discharges, and daily discharge frequency distributions. This relation was established for the Rhine at Lobith, at the Dutch-German border. The method is described by Asselman (1997, 1999).

7.4.2 Soil erosion and sediment supply to small streams

A first attempt to model soil erosion in the Rhine basin was carried out by Asselman (1997), who developed the Rhine Soil Loss Model (RSLM). The RSLM is based on the Universal Soil Loss Equation (USLE) developed by Wischmeier & Smith (1978). The RSLM was refined and expanded by Van Dijk & Kwaad (1999). The most important improvements are the application of a shorter time step, i.e. monthly instead of annually, and the introduction of a hillslope sediment delivery function, which accounts for storage of sediment at the base of slopes. The model is called the **R**hine model for evaluating effects of **E**nvironmental **C**hange **O**n **D**elivery of **E**roded soil to **S**treams (RECODES). The model is described in more detail by Van Dijk & Kwaad (1999).

7.4.3 Sediment transport through the channel network

From the sediment that reaches the drainage system, only a small part is transported downstream. A large part is deposited on the floodplains along the channel or in the channel itself. In this study, several methods were applied to estimate channel sediment delivery ratios in the Rhine and its tributaries. The results of the applied methods are summarised in the first column of Table 7.2. A plus sign indicates an efficient sediment delivery (little sedimentation), whereas a minus sign indicates inefficient sediment delivery (much sedimentation). Although the plus and minus signs provide a qualitative indication of CSDRs approximate values can be assigned to them. They range from: --- less than 10% to ++ 100% or more. The processes that are considered most important for the sediment delivery in a certain river reach (sedimentation in lakes, behind weirs, or on floodplains) are given in the other columns in Table 7.2. A plus sign indicates that the location is an important storage location, whereas a minus sign means that the storage location is not present or of little importance.

Table 7.2 Importance of different storage sites in different parts of the Rhine drainage basin

	Floodplains	Weirs	Lakes
Tributaries			
Neckar	+/-	++	+/-
Main	+/-	++	+/-
Mosel (France)	+/-	++	+/-
Mosel (Luxembourg & Germany)	-	+/-	+/-
Lahn	+/-	+	+/-
Ruhr	+/-	+/-	++
Main channel			
Upstream of Rheinfelden	+/-	+/-	+++
Rheinfelden – Maxau	+/-	++	-
Maxau – Worms	+	-	-
Worms – Kaub	+	-	-
Kaub – Andernach	-	-	-
Andernach - Rees	++	-	-
Distributaries			
Waal	++	-	-
Lek	+	+	-
IJssel	++	-	-

The results thus indicate that storage of sediment at high discharge by floodplain sedimentation is important in the Rhine downstream of Andernach. In the tributaries of the river Rhine temporary storage of sediment mainly occurs during periods of low flow, due to sedimentation behind weirs. Because sedimentation in the channel is important in large parts of the Rhine basin, a sediment transport model must be applied that allows for deposition of sediment behind weirs at low discharge. During periods of high discharge part of this material is picked up again and transported farther downstream.

7.4.4 Floodplain sedimentation

Sediment loss due to floodplain sedimentation is modelled using two approaches:
Sedimentation at the floodplains along the Rhine channel in Germany is modelled using a channel sediment delivery function In this equation the CSDR decreases with discharge:

$$CSDR = a * (Q_m)^b$$

with CSDR is the channel sediment delivery ratio, Q_m is the monthly average discharge and a and b are regression coefficients.
Sedimentation on smaller floodplain sections along the Rhine distributaries in the Netherlands is modelled using the SEDIFLUX model developed by Middelkoop & van der Perk (1998). A prerequisite for the application of the SEDIFLUX model is that *daily* suspended sediment transport estimates are available instead of monthly average estimates. Conversion of monthly sediment loads into daily sediment transport rates is carried out using the estimated monthly sediment load, the estimated daily discharge frequency distribution, and the relation between river discharge and suspended sediment concentrations. This method is described extensively by Asselman (1999).

7.5 Sediment transport and deposition under present climate and land use conditions

7.5.1 Sediment transport

The annual sediment load transported in the Rhine near Rees amounts to about 3.15 10^6 tons per year, whereas the computed sediment supply equals 11.73 10^6 tons year. This implies that the average channel sediment delivery ratio (CSDR) in the entire Rhine basin is about 27%. A more detailed analyses of channel sediment delivery ratios under present day climate and land use conditions in different parts of the Rhine is given in table 7.3. Sediment loads have been measured by the BfG at different locations in the river Rhine. Sediment contributions from tributaries are estimated from the downstream increase in measured sediment load in the main channel of the Rhine. When these increases in sediment load are compared with computed sediment supply, sediment delivery ratios can be computed for different parts of the river Rhine.

Table 7.3 Estimated channel sediment delivery ratios for different parts of the river Rhine and its tributaries under present climate conditions

Tributaries	Location	Comp. supply (10^6 t/yr)	Comp. CSDR (%)	Meas. load (10^6 t/yr)
Upstream Diepoldsau		0.71	502	-
	Diepoldsau	-	-	3.58
Aare		3.40	16	-
	Rheinfelden	-	-	1.11
Ill		2.14	36	-
	Maxau	-	-	1.16
Neckar		1.41	55	-
	Worms	-	-	1.40
Main, Nahe		2.09	62	-
	Kaub	-	-	2.16
Mosel, Lahn		1.35	99	-
	Andernach	-	-	3.48
Lippe, Ruhr		0.64	76	-
	Rees	-	-	3.15

Computed sediment supply includes sediment supply in smaller tributaries and from the hill slopes that directly border the Rhine between two gauging stations. To keep the table orderly, only the most important tributaries are named.

Channel sediment delivery ratios are high (about 100%) in the Mosel river. Moderate values of about 65 to 75% are found in the rivers Main and Nahe, and in the tributaries downstream of Andernach. Channel sediment delivery ratios are low in the rivers Ill and Neckar (36% to 55%). The lowest values however are obtained for the Alpine rivers such as the river Aare (16%). Sediment delivery in these mountain rivers is low due to sedimentation in lakes. The CSDR through the Bodensee for instance is less than 5%.

7.5.2 The sediment transport regime

The relation between suspended sediment concentration and river discharge is described by the rating curve technique. Multiplication of the discharge, the discharge frequency distribution, and the sediment rating curve, results in the sediment discharge curve. The area below the sediment discharge curve equals the total annual sediment load. The shape of the sediment discharge curve indicates how the total annual sediment load is distributed over different discharge stages. The curve peaks at the so-called effective discharge. This is the discharge at which the largest part of the annual sediment load is transported.

Figure 7.2 shows the sediment discharge distribution computed for the reference period 1960-1980. The observed discharge frequency distribution and the fitted sediment rating curve for the measurement period 1975-1991 are shown as well. The average total annual sediment load of the River Rhine at Rees during the reference period equalled $2.85*10^6$ t/yr. Figure 7.2 shows that under actual climate conditions most sediment is transported under moderate discharge conditions. The most effective discharge for sediment transport is about 2250 m^3/s, which equals the annual average discharge. Extreme discharges are not very important as only a limited percentage of the total annual load is transported at river discharges exceeding 6000 m^3/s.

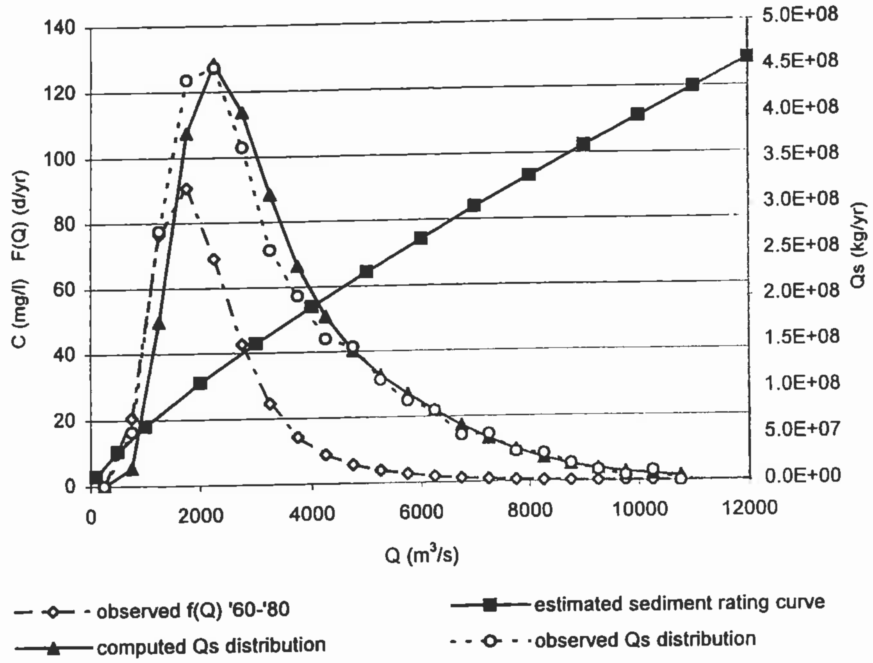


Figure 7.2 Sediment discharge curves established for Rees for the reference period 1960-1980

7.5.3 Floodplain sedimentation

Floodplain sedimentation under present climate and land use conditions was estimated for two floodplain sections along the river Waal, the main distributary of the river Rhine in the Netherlands. One floodplain section, the Variksche Plaat (VP), is a low lying floodplain section, not bordered by a minor river dike. As a result, the VP section is inundated annually. The other section, the Stiftsche Uiterwaard (ST) is protected from low floods by a minor river dike. Inundation starts at higher discharge than at VP and occurs less frequently. The computations were carried out with the SEDIFLUX model.

Spatial variability in computed annual sediment accumulation under present climate conditions is shown in figure 7.3. Sedimentation rates are maximum (more than 2.9 kg/m²) at VP. Within ST sedimentation rates are maximum in the upstream part (about 1.9 kg/m²) and minimum in the downstream part near the river dike (slightly more than 1.4 kg/m² on average). The average annual sedimentation at VP equals 2.22 kg/m², whereas at ST only about 1.29 kg/m² of sediment is deposited annually.

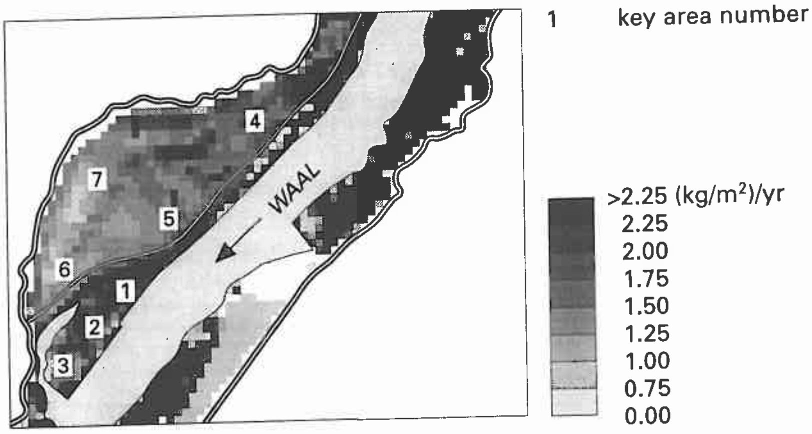


Figure 7.3 Computed present annual floodplain sedimentation at the Variksche Plaat (locations 1-3) and the Stiftsche Uiterwaard (locations 4-7), with $w_s = 7*10^{-5}$ m/s, and τ_c=2 N/m²

The SEDIFLUX model also was used to estimate the importance of different discharge stages on the total annual sediment accumulation. For 7 discharge stages sediment accumulation was calculated at the selected key areas (figure 7.3) and over the floodplain section as a whole. The results were plotted against discharge (figure 7.4). The discharge that yields on average the largest annual sediment deposition is called the effective discharge for sedimentation for the specific area.

The results in figure 7.3 indicate that the presence of a minor river dike has a major impact on the effective discharge for sedimentation. Consequently, the VP area has a lower effective discharge than the areas in ST, which are protected from low floods by a minor river dike. Also, areas located directly behind the lowest parts of the minor river dike have a lower effective discharge than locations at greater distance. Under present climate conditions the effective discharge for sedimentation varies between 5500 m³/s at the downstream end of VP and 6750 m³/s at some locations within ST.

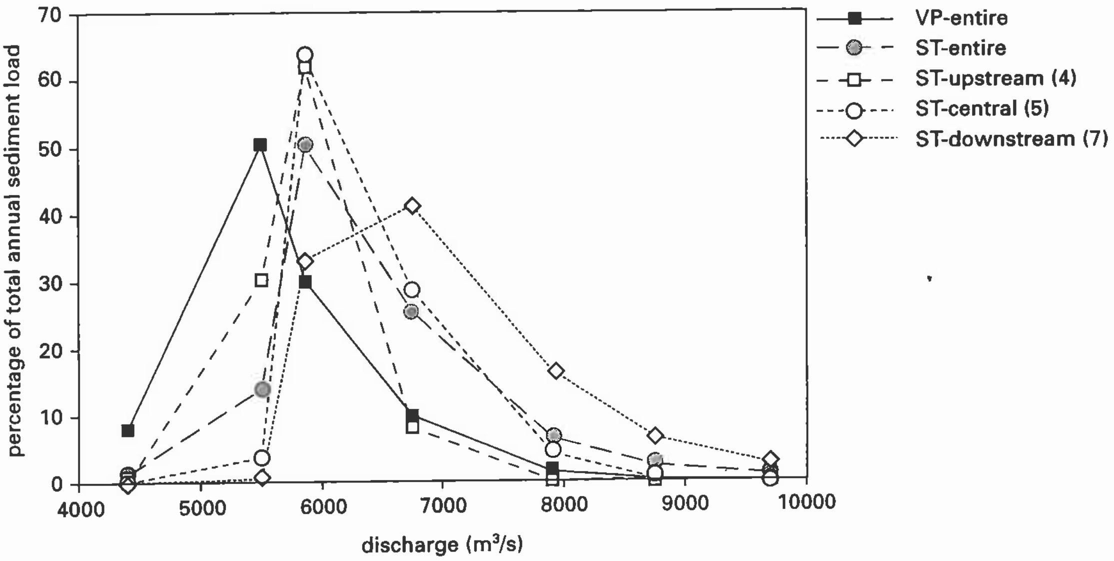


Figure 7.4 Percentage of annual sediment accumulation deposited at different parts of the Variksche Plaat and the Stiftsche Uiterwaard at different discharge stages under present climate conditions. Key area numbers are given in figure 7.3.

7.6 Sediment transport and deposition under changed climate and land use conditions

The aim of this section is to quantify possible changes in sediment transport, and floodplain sedimentation rates in response to expected changes in climate, land use, and river discharge. The climate change and land use scenarios applied in this study are described in more detail in chapter 3.

7.6.1 River discharge

Monthly average discharges were calculated using changes in monthly average temperature and monthly precipitation as given by the UKHI climate change scenarios. The annual average discharge near Rees during the reference period 1960-1980 was about 2240 m^3/s. According to the central estimate climate change scenario, an annual average discharge of about 2266 m^3/s is expected by the year 2100. It can thus be concluded that the annual average discharge will not change very much. Discharge variability, however, is expected to increase.

Expected changes in the daily discharge frequency distribution under scenario climate conditions are shown in figure 7.5. According to the central estimate for 2100, low discharges, less than 1500 m^3/s, and high discharges of 3500 m^3/s or more, are expected to occur more frequently, while moderate discharges of 1500 m^3/s to 3500 m^3/s are expected to occur less frequently. The lower and the upper estimates of changes in the discharge regime demonstrate that the uncertainty range around the estimated changes is large.

For instance, discharges of about 750 m^3/s occur about 20 days per year under present climate conditions. According to the central esimate for the year 2100 this value will increase upto about 32 days per year.

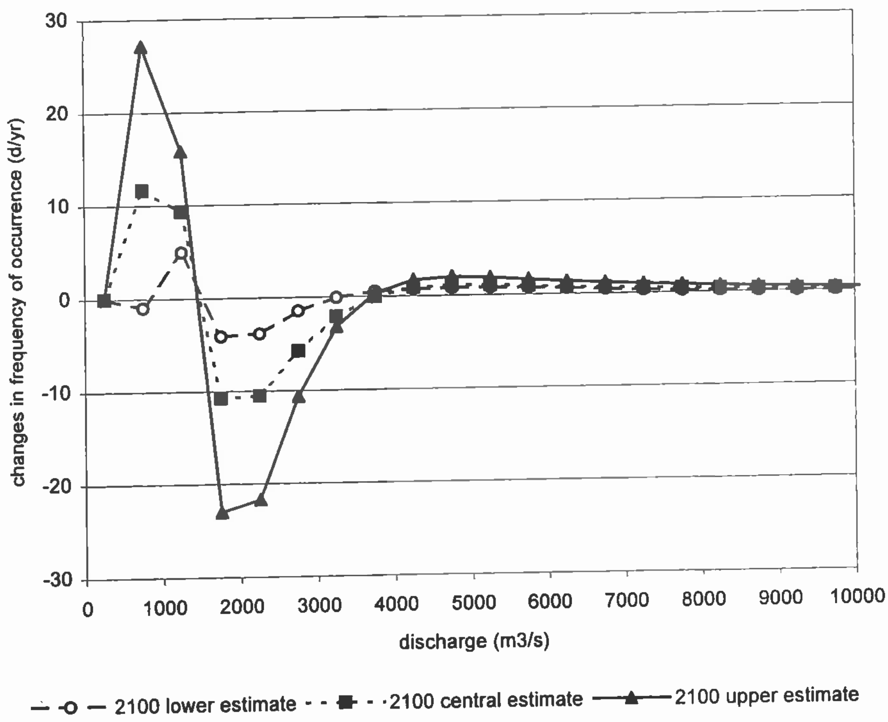


Figure 7.5 Changes in daily discharge frequency distribution under scenario climate conditions for the Rhine at the German-Dutch border

7.6.2 Sediment supply

Erosion and hillslope sediment supply under changed climate and land use conditions are estimated with the RECODES model by Van Dijk and Kwaad (1999. Two types of soil erosion scenarios were evaluated. These scenarios examine changes in erosion in different parts of the Rhine basin by the year 2100 under:
1) present climate conditions with autonomous changes in land use (referred to as the Central Projection or CP-scenario),
2) UKHI climate conditions with autonomous and climate induced changes in land use (referred to as the Central Projection Climate change or CPC-scenario)
Upper and lower limits of changes in sediment load are provided for scenario 2, using the lower and upper climate change estimates. This resulted in a total of 4 scenarios. Expected changes in sediment supply according to these scenarios are shown in table 7.4

Table 7.4 Expected changes in sediment supply under scenario climate and land use conditions in different parts of the Rhine basin by the year 2100. Changes are expressed as a percentage of present supply values

Location	Scenario 1	Scenario 2a	Scenario 2b	Scenario 2c
Alpen Rhine	220	240	257	284
Aare	7	30	38	54
Ill	-22	-43	-42	-35
Neckar	-13	-18	-12	11
Main	-33	-35	-31	-12
Nahe	-29	-23	-15	10
Mosel	-16	-23	-16	6
Lahn	-23	-21	-15	9
Ruhr	-21	-18	-14	11
Lippe	-24	-15	-4	27
Entire basin	0	5	12	31

1 = autonomous changes in land use only (CP land use scenario),
2a to 2c = changes in land use and climate, (a) lower (b) central and (c) upper estimate climate change scenarios for 2100, with CPC land use scenario,

7.6.3 Sediment loads of the river Rhine and its main tributaries

Average annual sediment loads

Scenario changes in hill slope sediment supply are used to estimate scenario sediment loads in the main tributaries of the Rhine. For these computations it is assumed that CSDR given in table 7.3 remain constant under changed climate conditions. The expected changes in sediment loads at different locations along the river Rhine are summarised in table 7.5.

As shown in table 7.4, total sediment supply upstream of Rees is expected to increase due to changes in land use and climate (12%, scenario 2b). This increase mainly is caused by a large increase in sediment supply in the Alps (more than 250%, table 7.4). This increase would have a significant impact on sediment transport near Rees when channel sediment delivery is not accounted for. However, when channel sediment delivery is accounted for, the sediment load at Rees is expected to decrease due to changes in land use and climate (scenario 2, table 7.5). A large part of the sediments that are supplied from valley slopes in the Alps is deposited. As shown in table 5.1 only 16% of the sediment that originates from the Alps reaches Maxau. Due to this inefficient sediment delivery, the impact of the large increase in sediment supply in the Alps has a limited impact on the sediment transport near Rees. Under present climate conditions the annual sediment load at Rees is about 2.88 10^9 kg (estimated average annual sediment load during the reference period 1960-1980). Under climate and land use conditions that are in accordance with the UKHI climate change scenario and the CPC land use scenario, the total annual sediment load of the Rhine at Rees is expected to decrease by 13% by the year 2100. The lower climate change projection results in a decreased sediment load by 19%. According to the upper climate change projection, an increase of about 9% is expected (scenarios 2a and 2c, table 7.5). When only autonomous changes in land use are accounted for, a decrease in total annual sediment transport by 17% instead of 13% is expected (comparison of scenario 1 and 2b, table 7.5).

The effect of climate change on the future sediment load can be estimated from the difference in sediment load estimated by the climate and land use change scenario (scenario 2), and the autonomous land use change scenario (scenario 1). The difference in total annual sediment load will be about 0.15 10^9 kg/yr. This means that due to climate change, the sediment load near Rees will be 0.15 10^9 kg/yr higher than when the sediment load is affected by autonomous changes only.

Table 7.5 Expected changes in average annual sediment loads under scenario climate and land use conditions in different parts of the Rhine basin by the year 2100

Location	Scenario 1	Scenario 2a	Scenario 2b	Scenario 2c
Diepoldsau	220	240	257	284
Rheinfelden	112	132	145	167
Maxau	31	31	37	52
Worms	7	5	11	31
Kaub	-16	-17	-12	8
Andernach	-17	-19	-13	8
Rees	-17	-19	-13	9

1 = no climate change scenario with CP land use scenario,
2a to 2c = UKHI climate change scenarios, with CPC land use scenario (lower, central, and upper climate change estimates for 2100).

Sediment transport regime

Expected changes in the annual sediment load transported at different discharges are shown in figure 7.6. According to all climate change scenarios less sediment will be transported at moderate discharges of about 2000 m^3/s. Sediment transport rates at high discharges, as well as low discharges will increase. Only when climate changes in accordance with the lower climate change estimate (scenario 2a), the total sediment load transported at high discharge will decrease. Comparison of the changes in the discharge frequency distribution (figure 7.5) with the changes in the sediment discharge frequency distribution (figure 7.6) suggests that changes in the sediment transport regime mainly are caused by changes in the discharge regime.

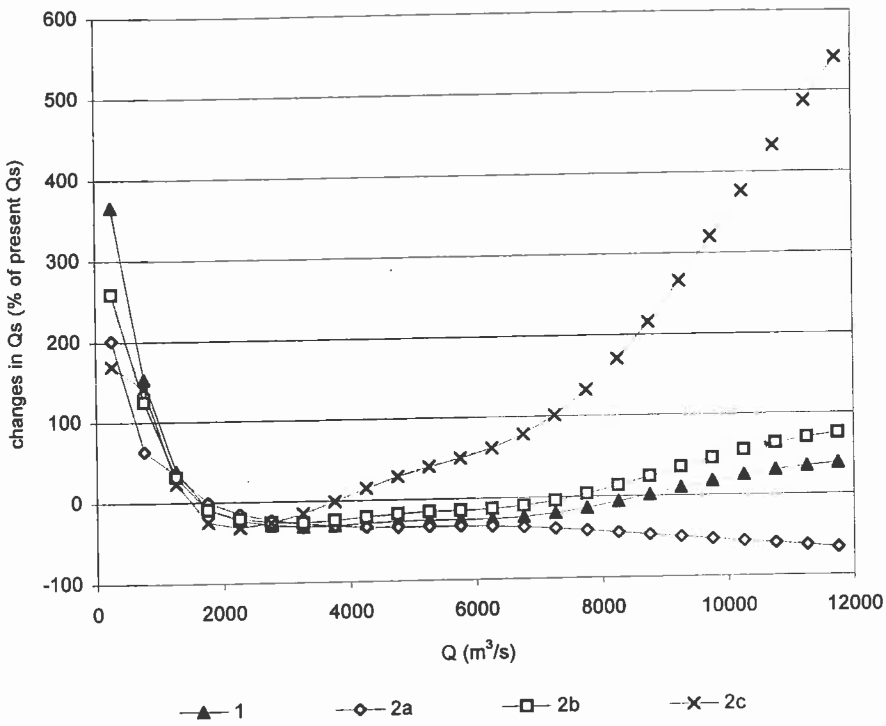


Figure 7.6 Expected changes in the annual sediment load transported at different discharge stages, scenario numbers are explained in table 7.5

7.6.4 Floodplain sedimentation

Average annual sediment accumulation
Expected changes in sedimentation rates due to changes in climate and land use are given in table 7.6.

The results can be summarised as follows:

- Under present climate conditions sedimentation rates are highest at VP (figure 7.3, table 7.6). Within ST sedimentation rates are maximum in the upstream part (location 4) and minimum in the downstream part near the river dike (location 7).
- In response to autonomous changes in land use, sedimentation rates are expected to decrease by about 45% (scenario 1, table 7.6b). As river discharge, and hence the duration of inundation, do not change, the reduction is entirely caused by reduced sediment loads at discharge stages of 5000-9000 m^3/s.
- Under changed climate and land use conditions (central estimate for the year 2100), sedimentation rates are expected to decrease (scenario 2b). Although the duration of floodplain inundation and sediment transport at very high discharge, exceeding 7500 m^3/s, are both expected to increase, floodplain sedimentation is expected to decrease. This decrease is caused by the decreasing sediment loads transported at slightly lower discharges, when the floodplains are only just inundated and the trapping efficiency of the floodplains still is high. The decrease in average annual sediment accumulation is strongest in the downstream part of VP (location nr. 3) since these moderate discharges of 4000 to 6000 m^3/s are most important for sedimentation at these low lying areas. At the downstream part of ST very high discharges are much more important for sedimentation. Hence,

at this location (nr. 7) changes in sedimentation are expected to be minimal.

- The lower and upper estimates climate change scenarios show that the uncertainty range due to uncertainties in the climate change scenarios is large (scenarios 2a and 2c).

Effective discharge for floodplain sedimentation

Figure 7.7 shows the effective discharge for sedimentation computed for the dowsntream part of VP. The curves vary in height, as the area below the curve is proportional to the total annual sediment accumulation. The shape of the curves for scenarios 1 and 1a is similar to the shape of the curve for the present situation. The curves for scenarios 2b and 2c have a different shape. I.e. the peak of the curves shifts to a slightly higher discharge. This implies that the importance of high discharges for sedimentation in this area is expected to increase. This probably is caused by a decrease in the sediment loads transported at the lower discharges, whereas the total annual sediment load transported at high discharge increases. The curves of the other areas are not shown because the shapes remain the same under all climate and land use change scenarios. In other words, although absolute changes in sedimentation differ for the various discharge intervals, the effective discharge for sedimentation will remain the same as under present climate conditions.

Table 7.6 Estimated floodplain sedimentation under present and scenario climate and land use conditions

a) Average annual sedimentation (kg/m²/yr)

Location	present	Scen. 1	Scen. 2a	Scen. 2b	Scen. 2c
1	3.09	1.69	1.99	2.68	4.70
2	2.26	1.24	1.47	1.96	3.41
3	2.50	1.41	1.62	2.10	3.50
4	1.85	1.02	1.21	1.60	2.77
5	1.51	0.81	0.98	1.35	2.45
6	1.47	0.79	0.95	1.32	2.40
7	1.37	0.69	0.84	1.36	2.83
VP total	2.75	1.55	1.78	2.34	3.95
ST total	1.65	0.88	1.05	1.51	2.85

b) Percentage change in average annual sedimentation (%)

Location	present	Scen. 1	Scen. 2a	Scen. 2b	Scen. 2c
1	0	-45	-35	-13	52
2	0	-45	-35	-13	51
3	0	-44	-35	-16	40
4	0	-45	-35	-14	49
5	0	-47	-35	-11	63
6	0	-46	-36	-10	63
7	0	-49	-39	0	107
VP total	0	-44	-35	-15	44
ST total	0	-47	-36	-8	73

Scenario numbers: 1) changes in land use only 2) changes in climate and land use (a) lower, (b) central and (c) upper estimate climate change scenario.

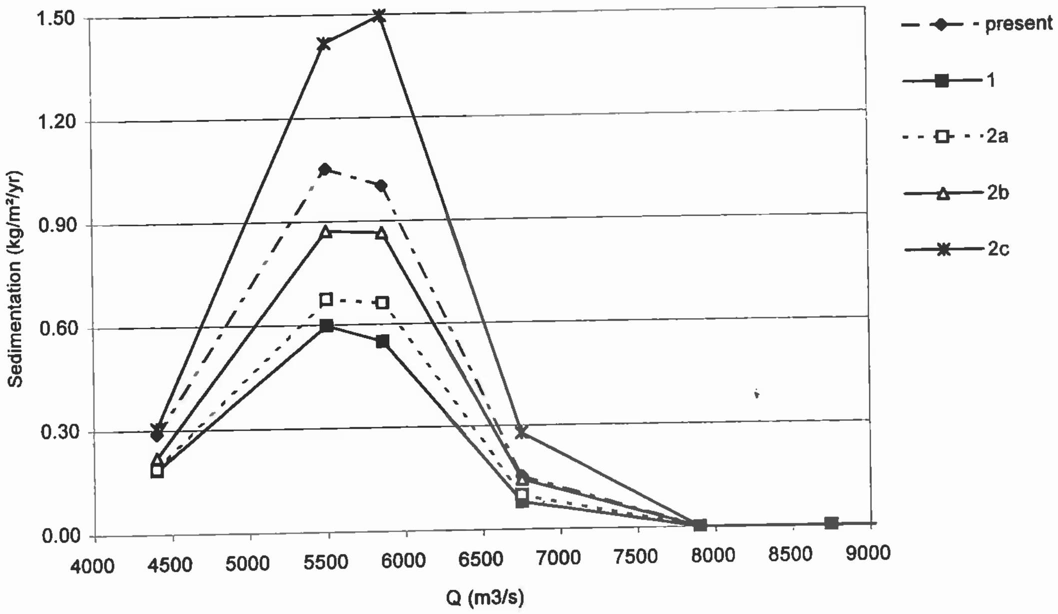


Figure 7.7 Annual sedimentation during different discharge stages at the downstream part of the Varikscher Plaat under present and scenario climate and land use conditions

7.7 Conclusions

Under present climate and land use conditions, the total annual sediment supply from the hillslopes into the channels in the entire Rhine basin is estimated to be about 11.7 10^6 tons. From sediment transport measurements that have been carried out by the Bundesanstalt für Gewasserkunde it was concluded that only about 27% of this amount reaches the German-Dutch border. The remaining part is deposited. In the Alpine rivers most sediment is deposited in lakes, such as the Bodensee. In the German tributaries much sediment is stored behind in channels, for instance behind weirs. In the Rhine downstream of Andernach floodplain sedimentation plays an important role.

When climate changes in accordance with the UKHI climate change scenarios, sediment supply in the Rhine basin is expected to increase in the Alps by about 250%. In the German part of the Rhine, sediment supply will decrease by about 5 to 40%. Averaged over the entire basin an increase of about 12% is expected.

Due to inefficient sediment delivery in the Alps, about 85% of the sediment is deposited in lakes and other storage locations, the increase in sediment supply in this area has a limited effect on the sediment loads near Rees. Although the average annual sediment load in rivers upstream of the Bodensee is expected to increase by more than 250%, the annual sediment load near Rees is expected to diminish by 13%. This decrease is expected to result in declining sediment loads at river discharges between 2000 and 7500 m^3/s at Lobith. The total amount of sediment transported at lower as well as at higher discharges is expected to augment.

Due to the decrease in sediment loads at discharges between 2000 and 7500 m^3/s, floodplain sedimentation is expected to decline by a 15% at relatively low floodplain sections that are inundated at discharges exceeding 5500 m^3/s. At floodplain sections were most sediment is deposited during periods of very high discharge, no decrease is to be expected.

8 Estimating the impact of climate change on peak flows in the River Rhine

Hans Middelkoop

8.1 Introduction

At present, the water balance model RHINEFLOW is operational, which calculates monthly and 10-daily discharges at the scale of the entire Rhine basin and the major tributaries of the river. To allow the determination of changes in peak flows, a daily time step is demanded. The development of a daily model for the entire basin, however, will be a very time-consuming task that demands large amounts of data. In the present study, therefore, two statistical downscaling techniques were applied in combination with the RHINEFLOW model to bridge the gap between the coarse water balance models and the daily time scale required to estimate changes in peak flows under changed climate conditions. The first method (referred to as the 'Conditional Peak Model') is based on empirical relationships between 10-daily or monthly average discharges and peak flows. This method was tested for the river Rhine at the Lobith gauging station, using a 94-year record of observed daily discharges. The second method (referred to as the 'Wavelet Disaggregation Model') comprises statistical disaggregation of series of 10-daily and monthly average discharges to the requested daily time step using the so-called wavelet technique. Using the RHINEFLOW model, the effects of climate change on the monthly and 10-daily average discharge of the Rhine were calculated. Subsequently, using the two statistical techniques, discharge extremes and their frequencies were estimated from the RHINEFLOW output. The study also considered uncertainties in the estimates, resulting from statistical variations in the baseline scenario, uncertainty in the model parameters and stochastic sampling procedures in the wavelet downscaling. Variations in the baseline scenario were based on a simple stochastic weather generator for a version of the RHINEFLOW-1 model with an 80-year base line. This is described in detail by Bruinsma (1996), Bruinsma & Kwadijk, (1997), Storms & Kwadijk (1997) and Middelkoop (1999).

8.2 Statistical relationships between average discharge and peak discharge: Conditional Peak Model

8.2.1 Method

The Conditional Peak Model is based on the relationships between monthly or 10-daily average discharges Q_m on the one hand and the peak discharge Q_p on the other hand (figure 9.1). The method has been developed by Kwadijk & Middelkoop (1994) for monthly discharges, and goes as follows. Monthly average discharges Q_m were derived from a record of daily measured Rhine discharges for the period 1901 to 1995 at the Lobith gauging station. The peak discharge Q_p is defined as the highest discharge observed in a month. All Q_m were classified into 15 classes C_k with a class width of 500 m^3/s. For each Q_m-class the frequency distributions of the Q_p-classes that occurred in this class were determined. The probability P_k of the occurrence of a peak discharge Q_p exceeding a given critical discharge Q_c, in a month with average discharge Q_m in class C_k, is then defined by equation [9.1]:

$$P_k(Q_p \geq Q_c, Q_m \text{ in } C_k) = [P(Q_m \text{ in } C_k)]*[P(Q_p \geq Q_c \mid Q_m \text{ in } C_k)] \qquad [9.1]$$

where: Q_p = peak discharge $[L^3T^{-1}]$
Q_c = critical discharge $[L^3T^{-1}]$
Q_m = monthly average discharge $[L^3T^{-1}]$
C_k = monthly average discharge class k (k = 1 - 15)

The first factor on the right hand side of equation [9.1] is the probability that a monthly average discharge Q_m falls in class C_k. The second factor on the right hand side is called the conditional probability of exceedance. For each Q_m-class, the probabilities of Q_p were parameterised using a log-normal PDF function, of which the average (μ) and standard deviation (σ) were estimated from the observed Q_p frequencies in each Q_m-class. The probability of a peak flood exceeding Q_c in any month is obtained by adding the joint probabilities for all Q_m classes k from equation [9.2]:

$$P(Q_p \geq Q_c) = \sum_{k=1}^{15} P_k(Q_p \geq Q_c, Q_m in C_k) \qquad [9.2]$$

The same procedure was carried out using 10-daily discharges obtained from the observed record instead of a monthly Q_m.

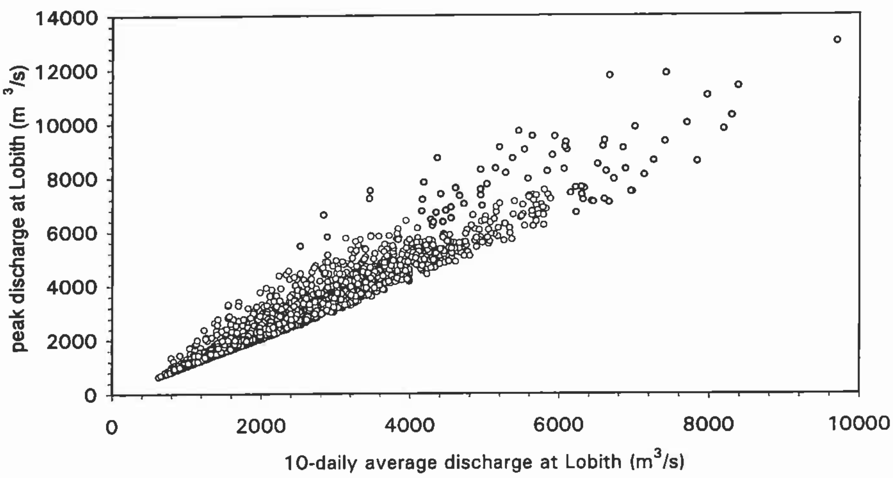


Figure 9.1 Relationship between 10-daily average discharge and peak discharge for the Rhine River at Lobith

In the application of the method, the monthly and 10-daily average discharges Q_m under changed climate conditions were calculated using the RHINEFLOW-1 and RHINEFLOW-2 models for changed climate conditions. By replacing the probabilities $P(Q_m$ in $C_k)$ in equation [9.1] by the scenario probabilities $P'(Q_m$ in $C_k)$, the peak discharge probabilities and the annual flow durations according to the scenario were obtained. The method was tested by using the conditional probabilities calculated from the wettest period of 25 consecutive years to estimate the frequencies of peak discharges for the driest 25-year period. The results agreed well with the observed values, indicating that the model is valid under the present day variability of the climate (Kwadijk & Middelkoop, 1994). However, the model results for larger climate changes may be less reliable.

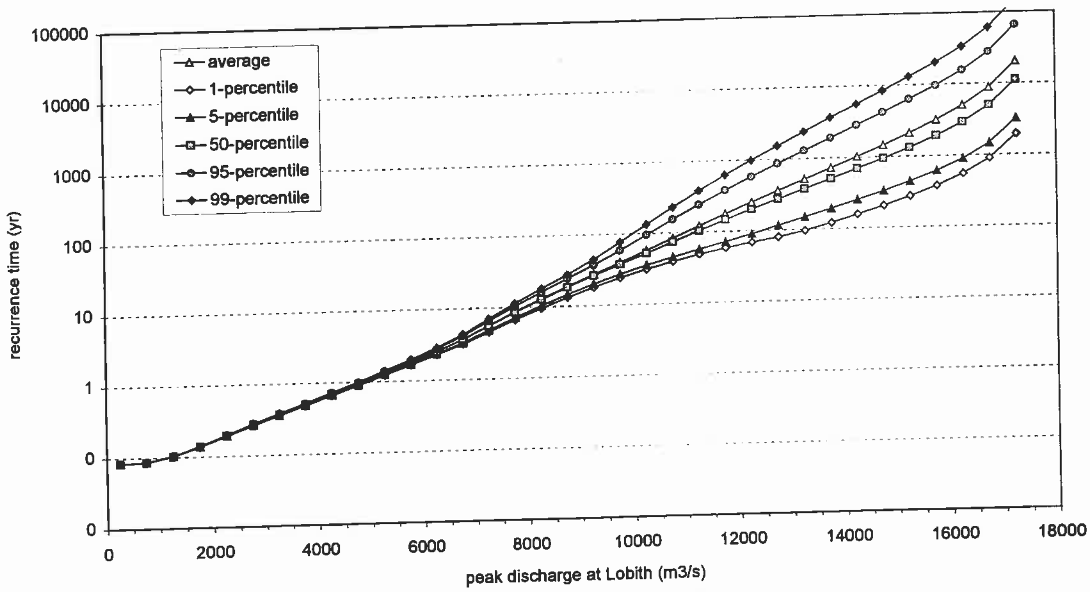
Uncertainties in the peak flow estimates resulted from uncertainties in the estimates of μ and σ of the PDF, and the base-line series of the RHINEFLOW model. Therefore a Monte Carlo analysis was carried out in the selection of μ and σ, and on the baseline series of the monthly RHINEFLOW-1 model

(Middelkoop, 1999; Schulze, 1999). From the resulting set of simulation results the minimum, average and maximum values, as well as the 5 and 95 percentiles were determined.

8.2.2 Results

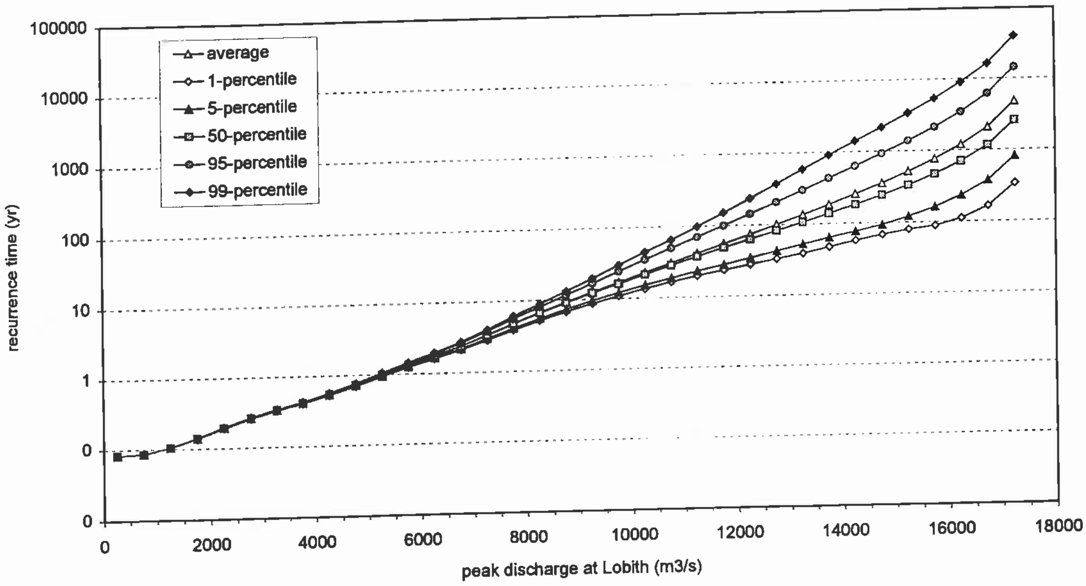
The recurrence times of the discharge peaks of the Rhine River at Lobith estimated using 10-daily basis agreed well with the estimates based on the observed maxima for discharge peaks with a recurrence time longer than one year. Simulation results obtained using the 10-daily RHINEFLOW-2 model for present-day climate and for two climate change scenarios, referred to as UKHI2050 (upper estimate for 2050; central estimate 2100) and UKHI2100 (upper estimate for 2100) are shown in figure 9.2. The results based on the average indicate that extreme peak discharges may increase by about 12% according to the UKHI2050 scenario, and by about 25% according to the UKHI2100 scenario.

The results and uncertainties due to the combined effect of uncertainties in the baseline scenario and the sampling of μ and σ, obtained using the RHINEFLOW-1 model for the central estimate climate scenario are given in figure 9.3. The estimated 95% confidence intervals around 100 to 1000-yearly peak flows are in the order of 3000 to 4000 m^3/s.

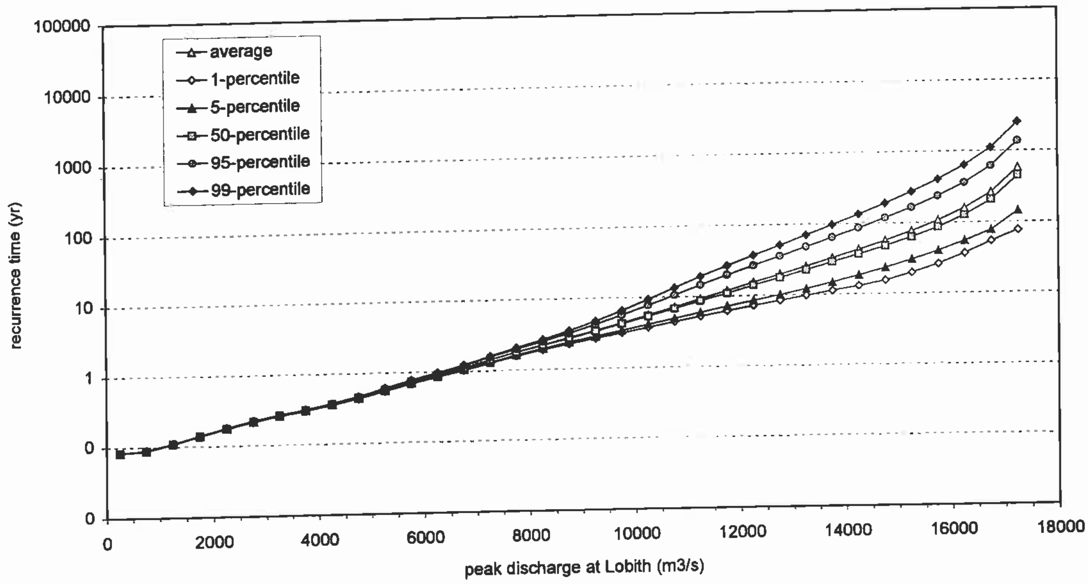


A Present climate; reference period 1960-1990

Figure 9.2 Simulation results for present day climate and two climate change scenarios, estimated using the Conditional Peak Model from 10-daily average discharges calculated using the RHINEFLOW-2 model



B UKHI2050 scenario (upper estimate for 2050, central estimate for 2100)



C UKHI2100 scenario (upper estimate for 2100)

Figure 9.2 - continued -

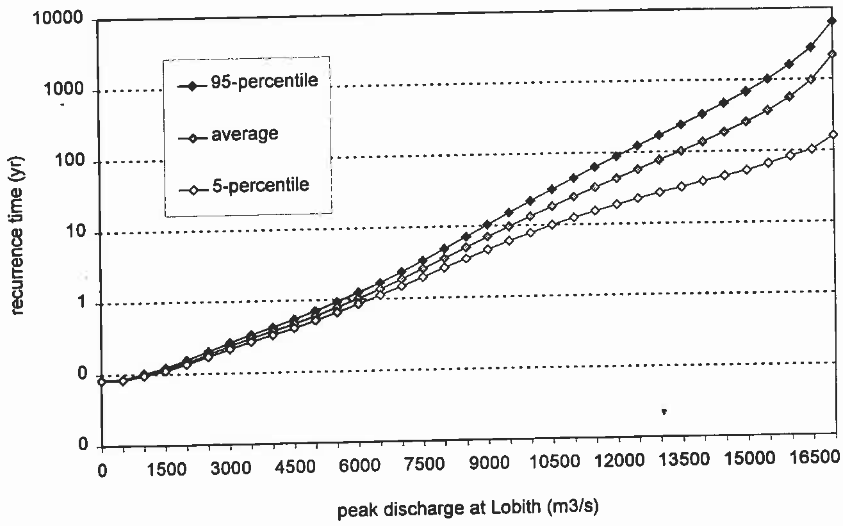


Figure 9.3 Simulated recurrence times of peak discharges of the Rhine at Lobith with estimated confidence interval. Monte Carlo simulation results for varying μ_i and σ_i in combination with 25 realisations of a 110 year baseline scenario for the extended RHINEFLOW-1 model for the UKHI2050 scenario (upper estimate 2050; central estimate 2100)

8.2.3 Conclusions

The estimates of peak flows from the RHINEFLOW model output using the Conditional Peak Model indicate that peak flows of the Rhine at Lobith will increase in response to climate change. Increases were found in the order of 15 % for the UKHI2050 scenario (upper estimate 2050, central estimate 2100), and as high as 25 - 40 % for the UKHI2100 scenario (upper estimate for 2100). The application of the CPM to the RHINEFLOW-1 model output resulted in a smaller increase of peak flows when compared to the result obtained for RHINEFLOW-2. However, the results obtained using the RHINEFLOW-2 model must be considered more accurate, because of the higher temporal resolution of the model, with a smaller gap to the daily time step to be bridged by the statistical downscaling. Due to model errors, variations in the baseline scenario and uncertainties in the estimates of the parameters of CPM, the uncertainty band around the estimates is in the order of 3,000 m^3/s for 100 to 100-yearly discharge peaks.

8.3 Disaggregation using Wavelets

Wavelet analysis is a more recently developed tool to analyse data series (Strang, 1993; Graps, 1995). It is a kind of Fourier analysis, with a major difference that it does frequency analysis on a local scale. Fourier analysis describes a process by sinuses and cosines that are continuous functions and that are non-zero between plus and minus infinity. In contrast, the basic functions for wavelet analysis are functions that are only non-zero within a bounded interval. Wavelet analysis is therefore an appropriate tool for describing processes that have most of the time values close to the average (or zero), interrupted by peaks (events). Wavelets allow investigating such time series on different scales. This makes the technique a useful tool for analysing disaggregation problems of discharge series. The application of wavelets for disaggregation of river discharge is more extensively described by Torfs (1995; 1997, 1998), Torfs & Middelkoop (1996) and Poppema (1997).

8.3.1 Method

Disaggregation means here decomposing an averaged process A_N produced by the RHINEFLOW model into the daily fluctuations that occurred during the averaging time interval N. The basic disaggregation step here is to halve the time scale N. By repeatedly halving the aggregation length N it is attempted to bridge the scale differences between the water balance models and the daily time-step (cf. figure 9.5). Since no information is available on the on the values of the disaggregated series, a stochastic disaggregation was carried out that, given the aggregated series, simulates a disaggregated series with the correct statistical properties.

Wavelets

The halving of the time scale was done using a prototype function, the so-called 'Haar-wavelet' that reflects the fluctuation around an average value at a time scale of N/2. The Haar wavelet is a step-function taking values 1 and -1 on the intervals [0,1/2) and [1/2,1) respectively (figure 9.4).

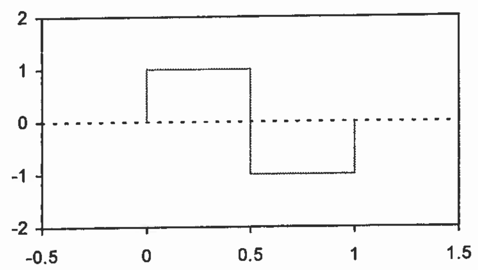


Figure 9.4 The Haar wavelet

To enable the reconstruction of the original time series using this Haar wavelet, it can be vertically scaled, shifted by n steps along the time axis, and the time scale N can be dilated (in the present application each time doubling N). The vertical scaling of all wavelets can vary not only at different time scales N, but also along the time axis. The time basis of an aggregated time series $A_N(n)$ can be halved down to the level N/2 by 'adding detail' in the form of a wavelet W_N. By repeatedly applying the wavelets in a cascade for all scales N, a step-wise downscaling is obtained in which N is halved in each step by adding and subtracting the accordingly wavelet coefficients $W_N(n)$ to the aggregation $A_N(n)$. This is illustrated in figure 9.5. On the left-hand side of the figure a series of daily discharges (bottom) is aggregated in a sequence of steps (A_N) until an aggregation length equal to 32 is reached (top). On the right hand side the wavelets W_N are shown that are each time the difference between two subsequent aggregations. The mother process (bottom left) can now be reconstructed from the 32-daily aggregation (A_{32}, top right) by subsequently adding all sets of wavelets W_{32}, W_{16}, W_8, W_4, W_2 to the aggregated process.

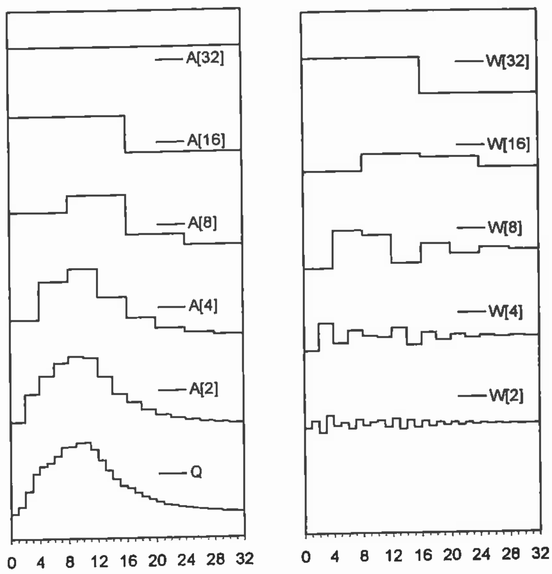


Figure 9.5 Disaggregating a discharge series from a 32-daily average to the daily time scale by step-wise halving the aggregation length (left, from top to bottom). At the right, the wavelets $W_N(n)$. These are obtained by subtracting A_N from A_{2N}. Addition of the wavelet series $W_1(n)$ .. $W_{16}(n)$ to the aggregated series A_{32} yields the daily Q series.

Disaggregation of stochastic time series

In this study, the 'mother process' river discharge is considered a stochastic process. Under assumption of stationarity, the random variables $A_N(n)$ and $W_N(n)$ are uncorrelated for all scales N and all translations n. In that situation, only the variance of the wavelet coefficients is to be investigated. The reduction of the variance with increasing length of N is summarised in the 'Variance Reduction Function' VRF (figure 9.6). This VRF also defines the amount of variance that must be added when halving the scale N by adding the wavelets W_N.

$$VAR[W_N(n)] = VRF(N/2) - VRF(N) \quad [9.3]$$

Analysis of the river discharges demonstrated that in each disaggregation step the variance of the wavelets linearly depends on the value A_N at the aggregation level next below. To account for this effect, a multiplicative model was introduced, using the Fractional Variance Reduction Function (FVRF, figure 9.6-right) (Torfs, 1998). The FVRF describes the *relative* amount of variance that has to be added to scale N of the process to get scale N/2.

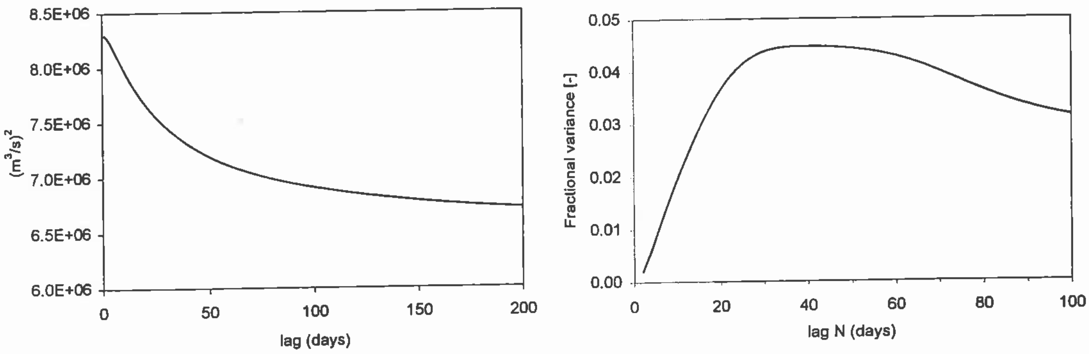


Figure 9.6 Variance Reduction Function (left); Fractional Variance Reduction Function (right) - winter discharge at Lobith

The FVRF and wavelet coefficients are determined from a daily time series of observed discharge. The downscaling of the aggregated time series to the daily scale starts from the highest aggregation length, and the wavelet model carries out a cascade of step-wise halving A_N by adding W_N. For each N the model generates n realisations for subsequent $W_N(n)$. To achieve a measure of the uncertainty resulting from the stochastic wavelet sampling in the disaggregation, 10 disaggregations were carried out for each scenario result of the RHINEFLOW-2 model.

To estimate the changes in peak flows of the Rhine at Lobith due to climate change, disaggregations were made for discharge series calculated using the 10-daily RHINEFLOW-2 model for present-day conditions and for two climate change scenarios: UKHI2050 (equivalent to the upper estimate projected to the year 2050 and central estimate for 2100) and UKHI2100 (equivalent to the upper estimate projected to the year 2100). Of each disaggregation the annual discharge maxima (in the hydrologic year, which is Nov – Oct) were determined. From these maxima, the recurrence times were calculated and plotted in a graph for comparison.

8.3.2 Disaggregation results for the Rhine at Lobith

Reconstruction of discharge peaks

The disaggregation results for the Rhine at Lobith obtained from 10-daily averages are shown in figure 9.7. Daily discharge peaks are clearly higher than the 10-daily averages. Disaggregation from the monthly scale requires two more steps than starting from a 10-daily basis, resulting in poorer estimates of individual discharge peaks. The disaggregation results obtained for changed climate conditions show a clear increase of the discharge peaks, particularly for the UKHI2100 scenario (figure 9.8). Because of the stochastic nature of the disaggregation method, the increases are not the same for all peaks; occasionally, a peak may have become even lower.

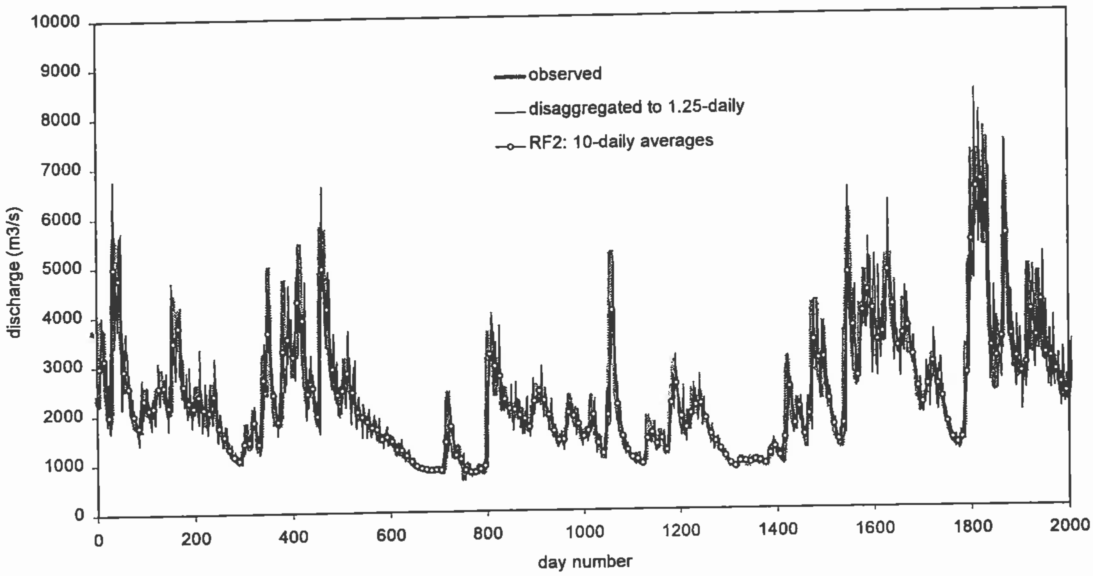


Figure 9.7 Disaggregation result for the Rhine at Lobith starting from 10-daily average discharges - present situation

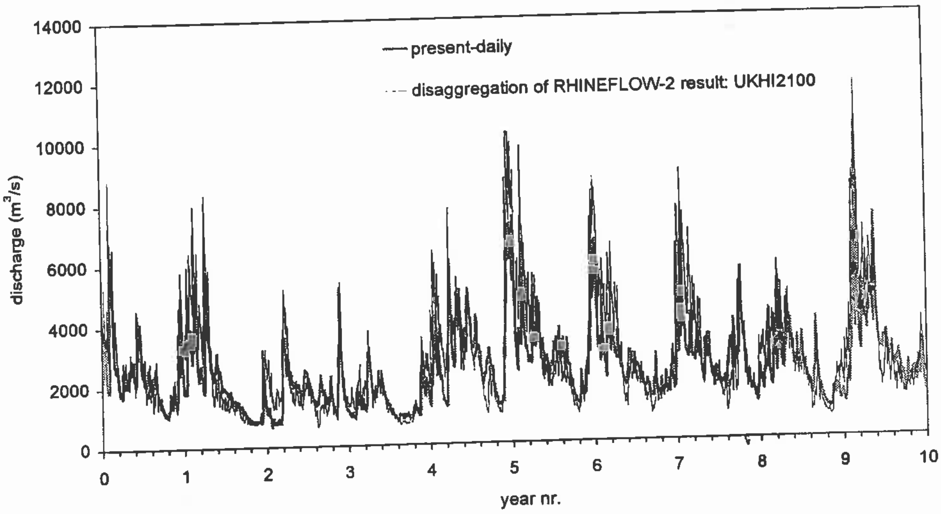


Figure 9.8 Disaggregation of the 10-daily RHINEFLOW-2 model result for the UKHI2100 scenario

Impacts on peak flow recurrence times

The peak flow recurrence times obtained for the changed climate conditions (figure 9.9) indicate a clear increase in peak flows. Under conditions of the UKHI2050 scenario the magnitude of peak flows with a >10-year recurrence time increases by about 8%, and under the UKHI2100 by about 25%. The increase for the UKHI2100 scenario is thus more than proportionally larger than the increase for the UKHI2050 scenario. The wavelet sampling resulted in a variation of peak flow magnitude in the order of 1000 to 1500 m^3/s, with a larger variation for the UKHI2100 scenario. Still, the increase in peak flows due to climate change is large when compared to the sampling uncertainty.

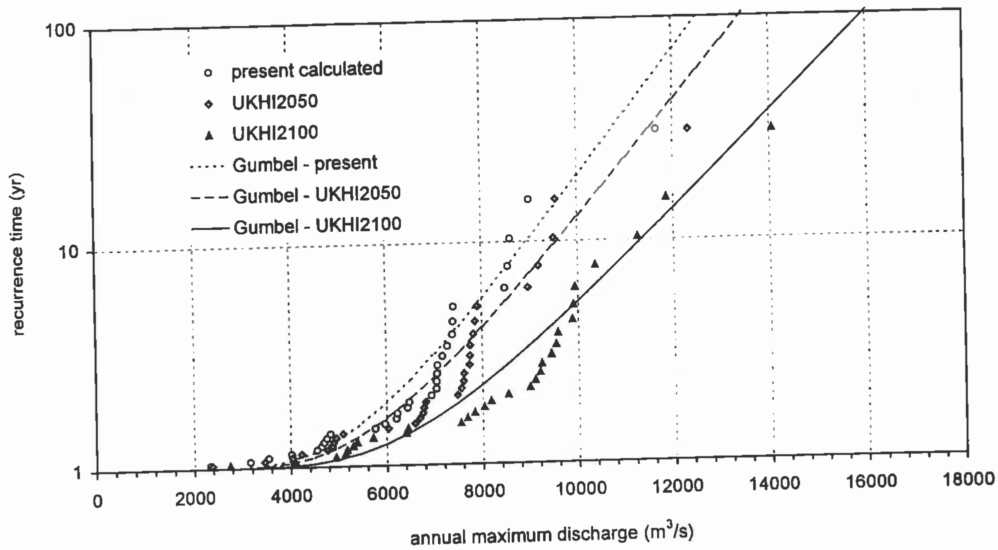


Figure 9.9 Peak flow recurrence times for present situation and the UKHI scenarios, obtained using the RHINEFLOW-2 model on the basis of the 1960-1990 reference period. Gumbel distributions have been fit for extrapolation to a 100-year recurrence time

8.4 Conclusions

Method

In spite of the straightforward approach of the Conditional Peak model, the method yields good results in estimating peak flow probabilities of the river Rhine at Lobith. The model, however, does not consider the statistical characteristics at intermediate aggregation levels and needs al long sampling record (>95 years) for parameter estimation. The model results are sensitive to uncertainties in the parameter estimates for extreme flows. The Wavelet Disaggregation Model is based on variances over the entire range of temporal scales of the process. It does not result in a day-to-day reproduction of the original series, but yields a stochastic disaggregation with the correct variances at all aggregation levels. Although discharge peaks are not explicitly incorporated in the statistics used, the method yields reasonable estimates of the magnitude of peak flows.

Changes in peak flows

Table 8.1 summarises the estimated changes in peak flows obtained using the 10-daily RHINEFLOW model in combination with the statistical downscaling. Climate change is expected lead to an increase of peak flows of the Rhine at Lobith. The Conditional Peak Model resulted in an increase of 17% for peaks with a 100-year recurrence time for the UKHI2050 climate change scenario, and for an increase up to 40% increase under conditions of the extreme UKHI2100 scenario. The wavelet downscaling resulted in more moderate increases: 8 (%) for the UKHI2050 scenario and 30% for the UKHI2100. Given the difficulties in the parameter estimation of the Conditional Peak Model for extreme discharges, the increases obtained using this method may be over-estimates when compared to the wavelet disaggregation results.

Uncertainties

Estimates of future magnitudes or frequencies of extreme discharge peaks are surrounded by several uncertainties that are different in nature and magnitude:

- Uncertainties related to the rate and magnitude of climate change.
- Systematic model errors in the RHINEFLOW model.
- The stochastic nature of the present-day climate.
- Uncertainty in the downscaling process of the RHINEFLOW-2 output

These uncertainties were reflected in the differences between the climate scenarios, and the uncertainty bands resulting from the sampling of the base line climate series, the Conditional Peak Model parameters and Wavelets. The downscaling uncertainty for the extreme UKHI2100 scenario was generally larger than for present-day climate. When considering only the effects of *changes* in climate, however, the bandwidth indicating total uncertainty gives an overly pessimistic indication of the model results. Finally, systematic errors were to some extent eliminated by calculating only the *changes* in average flows and discharge peaks.

Table 8.1 Estimates of changes in peak flows and uncertainty intervals of the estimates of the model results for two climate change scenarios, based on downscaling of the 10-daily RHINEFLOW-2 model using the Conditional Peak Model and the Wavelet Disaggregation

		UKHI2050: Upper estimate 2050, Central estimate 2100	UKHI2100: Upper estimate 2100
Conditional Peak Model			
Increase of peak flows with a 10-year recurrence time	(%)	13	40
Estimated increase of peak flows with a 100-year recurrence time	(%)	17	40
Estimated increase of peak flows with a 1000-year recurrence time	(%)	12	25
Width of 95% confidence interval around 10-y peak flows	(m^3/s)	800	2,000
Estimated width of 95% confidence interval around 100-y peak flows	(m^3/s)	3,000	2,500
Wavelet Disaggregation			
Increase of peak flows with a 10-year recurrence time	(%)	5	25
Estimated increase of peak flows with a 100-year recurrence time	(%)	8	30
Width of uncertainty interval around 10-y peak flows	(m^3/s)	800	1,100
Estimated width of uncertainty interval around 100-y peak flows	(m^3/s)	2,500	2,500

Scenarios for future design discharge under changed climate conditions

By applying the estimated changes in peak flows to the present-day design discharge, a set of scenarios for the design discharge of the Rhine at Lobith (which is here defined as the 1250-yearly discharge) was established (table 8.2). In accordance with the climate change scenarios that were the basis of this study, the scenarios comprise a lower, central and upper estimate for the design discharge, projected to the years 2050 and 2100.

- The *central estimate* is based on the 'central' climate scenario with a 2°C warming over the next century. The design discharge increases over the next century from 16,000 m^3/s to 16,500 m^3/s in 2050 and further to 17,500 m^3/s until the year 2100.
- The *lower estimate* envisages a minor climate change; the design discharge increases over the next century only by 500 m^3/s.
- The *upper estimate*, representing a major climate change with a 4°C warming, will lead to a major increase in the design discharge, which ends up with a value of at least 20,000 m^3/s by the year 2100.

It should be stressed here that these values are based on statistics of discharge volumes, without any hydraulic routing taking into account. It is very uncertain whether it is physically possible that a peak discharge of 20,000 could reach the Lobith gauging station. These estimates also assume that no measures for flood reduction are taken. Given these assumptions and the uncertainties around in the model results, particularly for the extreme scenario, these estimates must be interpreted as *scenarios* for the design discharge, which should be used in scenario studies for long-term river management or floodplain development.

When comparing these figures to previous estimates of the impact of climate change on the design discharge of the river Rhine (Kwadijk & Middelkoop, 1994; Parmet et al., 1995; Werkgroep Klimaatverandering en Bodemdaling 1997; Grabs et al., 1997), the following conclusions can be drawn:

- The present study provides insight in the magnitude and sources of the uncertainties around the estimates;
- The present study further underpins the changes in design discharge according to the central estimate projected to the years 2050 and 2100 indicated in previous studies (e.g. Grabs et al., 1997; Werkgroep Klimaatverandering en Bodemdaling, 1997);
- Estimates for extreme climate scenarios show a more than proportionally larger increase in peak flows, resulting in higher upper estimates of the design discharge for the year 2100 than previously assumed. Climate impact studies that envisage a 100-year time horizon, therefore, should consider as extreme scenario a design discharge in the order of 20,000 m^3/s, instead of 18,000 m^3/s as is presently done in Rhine studies (e.g. Silva & Kok, 1996).

Table 8.2 Scenarios for the design discharge of the Rhine at Lobith (recurrence time = 1250 year) resulting from climate change

Projection year	Current (m^3/s)	Lower estimate (m^3/s)	Central estimate (m^3/s)	Upper estimate (m^3/s)
2001*	16,000			
2050		16,250	16,500	17,500
2100		16,500	17,500	20,000

** in 2001 the design discharge will be re-established by the Minister. It is presently estimated that this discharge will equal about 16,000 m^3/s*

9 Implications for landscape planning alternatives for the River Rhine floodplains

Hans Middelkoop
Hendrik Buiteveld

9.1 Introduction

The river Rhine and its embanked floodplain fulfil many functions for the Netherlands. Flood defence, transport, ecological recovery, agriculture, recreation, sand an clay extractions, preservation of cultural and historical values, dredging and spoil disposal, these all must be accommodated in the finite space along the rivers. Climate change may lead to an increase of the design discharge of the lower river Rhine. Depending on the rate and magnitude of the assumed climate scenario the design discharge may increase over the next century from about 16,000 m^3/s to over 18,000 m^3/s. Climate-induced increases of peak flows demand an increased storage and discharge capacity of the high-water bed and thus are expected to raise constraints to the room available for the other river functions.

Over the past years various measures have been proposed for the different interests of the river functions (figure 10.1). To reduce the risk of floods, measures should be taken that reduce the water levels during periods of high river discharge. Examples are: lowering the floodplain surface, removing obstacles of the water flow, removing minor embankments, digging secondary channels, lowering groynes, displacement of river dikes. Only in case when other measures are unsuccessful to reduce water levels, the river dike must be enforced. Ecological recovery plans consider converting agriculture land into natural habitat, promoting greater exchange of water and sediment between the main channel and the flood plain, re-establishment of riverine forest, secondary channels and natural river banks. Modifications to the main channel would improve conditions for inland navigation. Agriculture benefits from summer embankments and raised flood plains, as agriculture land needs protections from floods during the growing season. And, in areas of special cultural or historic interest, it may be best to leave things as they are. Sometimes, a measure can serve several purposes at once: lowering the flood plain not only reduces flood water levels, but also allows wetlands to develop. On the other hand, it may involve destruction of a culturally or historically valuable landscape. It is evident that different interests might result in different measures taken in the floodplain area. The main question is then; how should different interests be weighed up, and what measures can reasonably be carried out, and where?

This study explores for different landscape planning alternatives to what extent they are sufficiently flexible and provide sufficient opportunities for increasing the flow capacity over the next decades, without denying the typical character and the vision behind a strategy. For example; if we choose to preserve the culture landscape as much as possible in the landscaping, to what extent, both in time and in magnitude, can we indeed create sufficient storage and flow capacity along the rivers without the affecting valuable areas or without large-scale dike raising? Or, does an alternative allow to implement measures in due time to keep up with the increasing design discharge? And, finally, what are the consequences for the other river functions if we have to adapt our landscape planning strategy for increasing design discharge?

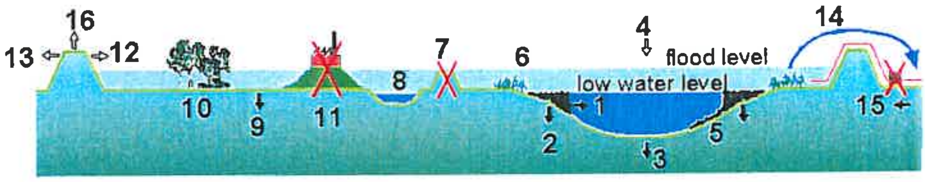
The main objective of this study was twofold:

1. To explore to which extent additional measures for reducing floodwater levels can be taken within different landscaping alternatives to keep up with increasing design discharge due to climate change.
2. To evaluate the implications of these adaptations for the other functions of the high-water bed of the river.

9.2 Methods

Landscape planning

The impact of climate-induced increases of the design discharge on the river functions safety, nature, agriculture, recreation and the consequences for the preservation of valuable landscapes was evaluated for three 'prototype' landscaping alternatives described in the Landscape planning study for the Rhine (LPR) by Silva & Kok (1996). Each alternative consists of a combination of measures (figure 9.1) and also aims at preserving current safety levels, but has its own emphasis: preserving current land use, nature development based on the so-called 'Target-situation' for ecological development (Postma et al., 1996), or preserving culturally or historically valuable landscapes. Figure 9.2 gives a landscape impression of these three LPR alternatives. A gradually increasing spatial demand to make way for the river in the case the design discharge increases in response to climate change may have different implications for different alternatives.



1 = narrowing the main channel	9 = lowering floodplain surface
2 = lowering of groynes	10 = nature development
3 = dredging	11 = removing raised areas
4 = redumping sediment	12 = dike reinforcement
5 = permanent bottom layer	13 = dike repositioning
6 = natural river bank	14 = retention outside winter-bed
7 = removing summer embankment	15 = obstruction lateral inflow
8 = digging a secondary channel	16 = dike raising

Figure 9.1 Schematic cross section of the main river channel and the embanked floodplain. The numbers indicate the various measures for nature development, inland navigation and flood water level reduction that can be taken.

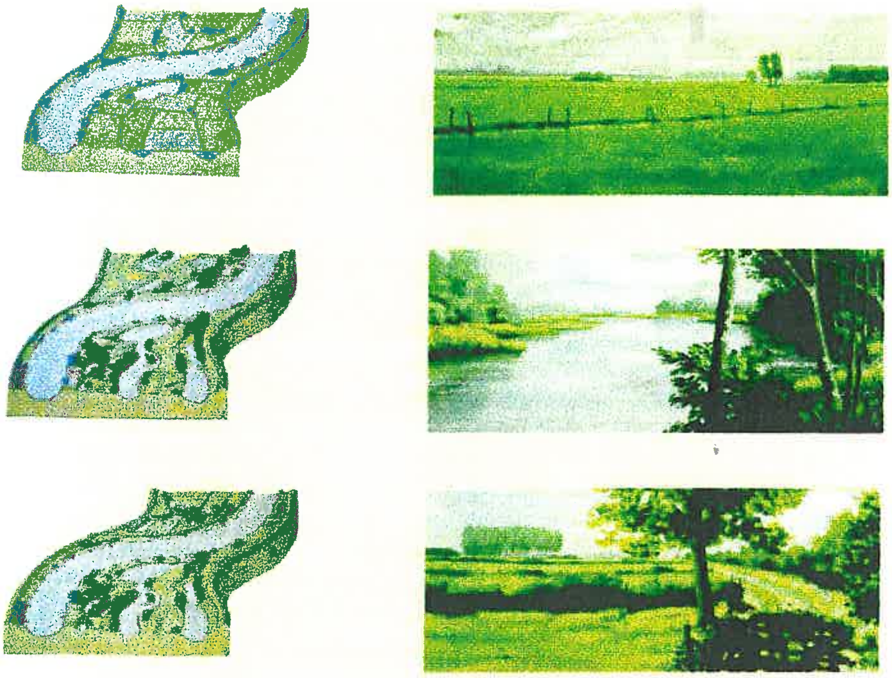


Figure 9.2 Landscape impressions according to three 'visions': Safety with current land use (top), Nature development (middle), Nature plus culture landscape (bottom).

The three landscaping alternatives were implemented according to the allowed measures for increasing design discharges. In each step, additional measures were implemented such that they compensated the higher flood water levels (table 9.1). As a first approach, the proportions of the total Rhine discharge distributed over the three Rhine branches at the bifurcation points has been set constant. Some assumptions were made on the rate at which measures can be implemented:

- Due to trading mechanisms in the selling of clay and sand, it is assumed that a volume of 1 million cubic metres overbank clay and 2 to 4 million cubic metres sand can be excavated from the floodplain area each year (Termes et al, 1998).
- Considering the time needed for planning, design and the actual ground work, it is assumed that each year only one side channel can be realised.
- Douben (1995) has identified a total of 88-km river stretches where widening the floodplain by dike displacement potentially is feasible. For the year 2050, it is assumed that dike displacement can be realised only at 25% of these stretches, the total 88-km only by the year 2100.

Applying additional measures or applying the measures over larger areas than indicated in the table means that the typical character or vision behind the variant is violated. So, when the measures for flood reduction allowed within the character of an alternative are insufficient to compensate for the increased design discharge, the maximum room available for flood protection within the alternative is reached. Then, the choice is either to deny the starting-point of the alternative in further implementation of measures, or to start to raise the river dikes.

Table 9.1 Summary of the starting-points of the landscape planning alternatives and their allowable measures in order of subsequent application

Alternative	Starting-point	Allowable measures
Safety with current land use (S)	• preservation current land use • no increase of hydraulic roughness • preservation of minor embankments	1. Removing of raised areas 2. Differentiated floodplain lowering up to 0.5 m above the median river water level 3. Widening the floodplain by dike displacement, up to 25% of the total 88 km in 2050
Nature development (N)	• target situation for nature development • introduction of natural floodplain vegetation • lowering floodplain	1. Implementation of vegetation (expressed by its hydraulic roughness) according to the 'target-situation' for nature development 2. Removal of minor embankments and large-scale floodplain lowering by 1 m 3. Further differential floodplain lowering down to 0.5 m above the median river water level 4. Replacing hydraulic rough vegetation by 'smooth' vegetation, until the present roughness is reached
Nature plus culture landscape preservation (LNC)	• culturally or historically valuable landscapes remain unaffected • application of target situation for nature development on remaining areas	1. Implementation of vegetation (expressed by its hydraulic roughness) according to the 'target-situation' for nature development 2. Leaving unaffected 3. At culturally or historically less valuable floodplain sections: removal of minor embankments and large-scale floodplain lowering by 1 m, 4. Further differential lowering these floodplain sections down to 0.5 m above the median river water level

Scenarios for design discharge

Three climate change scenarios are considered here: a central estimate, a lower and upper estimate, projected to the years 2050 and 2100. Since the design discharges that result from these climate scenarios cannot be determined with high precision (cf . Middelkoop, 1999), a limited number of plausible scenarios for the design discharges corresponding to the climate change projections was adopted (figure 9.3). Within the framework of the Rhine Action Programme (IKSR, 1997), several flood protection measures have been considered or decided upon. These include retention basins along the Oberrhein (upstream of Worms) and along the Niederrhein in Nordrhein-Westfalen. Janssen & Pakes (1997) and Van Haselen (1997) have carried out estimates of the efficiency of retention within the Netherlands on reducing the design discharge of the Rhine. From these studies, two straightforward scenarios for the net effect of retention measures on the design discharge were established: (1) a pessimistic scenario that assumes no reduction until the year 2050 and a reduction by 500 m^3/s by the year 2100; (2) a scenario that assumes a net reduction equal to 500 m^3/s by the year 2050 and 1000 m^3/s by the year 2100. By combining the increase in the design discharge due to climate change with the potential reduction of the design discharge at Lobith as a result of retention measures, two sets of scenarios for the net design discharge at Lobith were established. These are summarised in table 9.2.

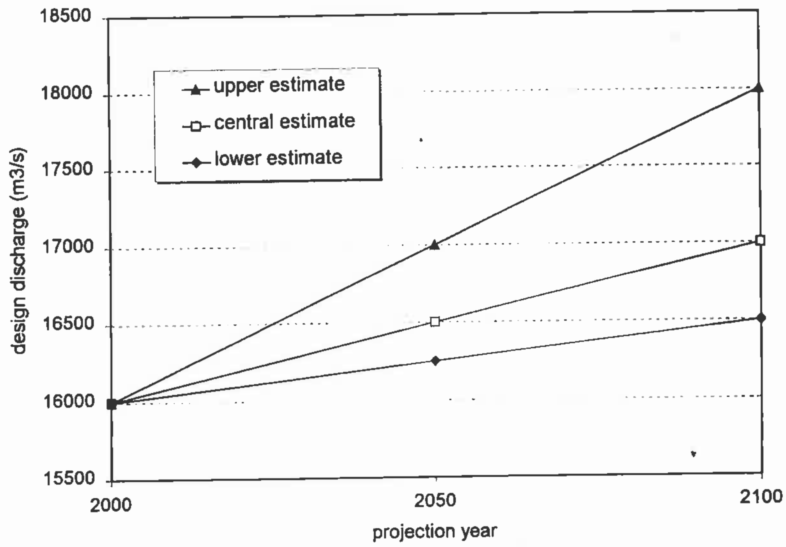


Figure 9.3 Schematic representation of the scenarios for design discharge resulting from climate change only

Table 9.2 Design discharges (in m³/s) according to the combined climate change and retention scenarios projected to the years 2050 and 2100

Climate scenario	Reference year 2000	Projection year 2050		Projection year 2100	
		Retention scenario 1	Retention scenario 2	Retention scenario 1	Retention scenario 2
Lower estimate	16,000	16,250	15,750	16,000	15,500
Central estimate	16,000	16,500	16,000	16,500	16,000
Upper estimate	16,000	17,000	16,500	17,500	17,000
Extreme	-	-	-	-	18,000

Evaluation of implications

For all alternative and scenarios, the implications for the river functions have been determined using the LPR decision support system (Silva & Kok, 1996; Buijsrogge et al., 1996). The criterion used to assess to what extent an alternative is able to cope with an increased design discharge is the length of the river stretches over which the design water level do not exceed the present-day reference design water levels. Subsequently, for each alternative and scenario the implications for the other river functions have been determined in terms of changes in water levels, areas of different land use and vegetation types, volumes of excavated clay, sand and polluted deposits, area available for recreation, and cost of the measures. The estimation of cost and effects has been based on the methods and estimates given in Kok et al. (1996) and Silva & Kok (1996).

9.3 Results

9.3.1 Reference situation 2000

The current landscape and water levels resulting from a design discharge of 15,000 m³/s have been used as a base line for comparing the effects of landscaping measures. Table 9.3 shows the increases in water levels calculated with the present-day landscape for varying increases of the design discharge, which might result from climate change. The landscaping alternatives and their associated measures must compensate these increases.

Table 9.3 Increase in flood water levels with reference to the water levels resulting from a design discharge equal to 15,000 m^3/s under present-day conditions for different scenarios of increased design discharge. In all cases small scale hydraulic obstacles are assumed to be removed.

	15,500	16,000	16,500	17,000	17,500	18,000
Bovenrijn – Waal	-0.1 – 0.1 m	0.1 – 0.2 m	0.2 – 0.3 m	0.3 – 0.4 m	0.4 – 0.5 m	0.5 – 0.65m
Nederrijn – Lek	-0.2 – 0.1 m	0 – 0.1 m	0.1 – 0.2 m	0.2 – 0.3 m	0.3 – 0.4 m	0.35 – 0.6 m
IJssel	-0.05 – 0 m	0 – 0.1 m	0.1 – 0.2 m	0.2 – 0.3 m	0.2 – 0.4 m	0.2 – 0.6 m

9.3.2 Results for the landscaping alternatives

Compensation of design water levels

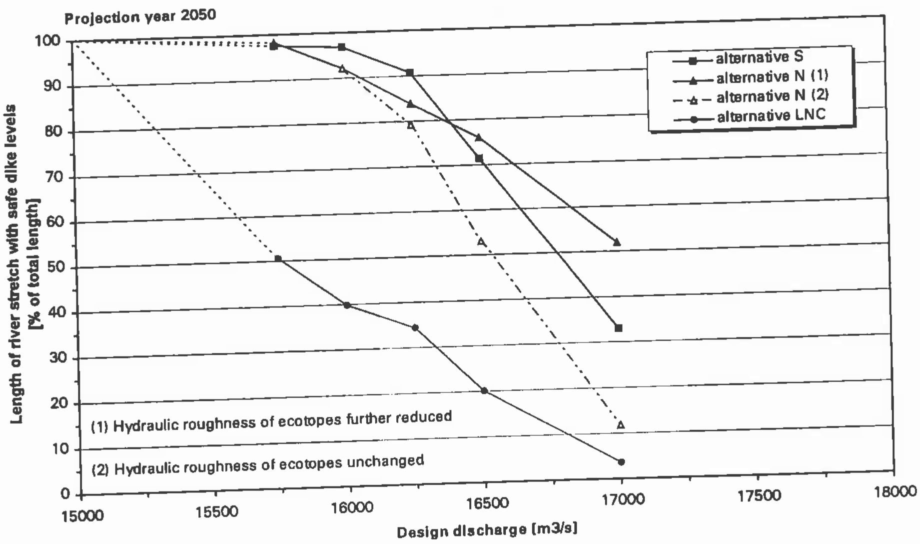
Figure 9.4 shows for all landscaping alternatives the length of the river stretches where the current design water levels are not exceeded in the case of increasing peak flows, expressed as percentages of the total length of the Rhine branches. The alternative 'LNC' provides the least overall possibilities for lowering flood water levels, regardless the projection year. Particularly along the River IJssel, with large valuable areas, water levels remained too high. The largest and most efficient total reduction of water levels over all river branches could be achieved when excavating the allowable amounts of clay and sand only along the Nederrijn and Waal branches, leaving the IJssel floodplains unaffected. The major reduction already by a design discharge of 16,000 m^3/s is a consequence of leaving the IJssel floodplains undisturbed at first. This causes an increase of water levels over about 40% of the total river length.

The alternatives S and N allow to compensate water levels adequately for design discharge increasing to about 16,000 to 16,250 m^3/s. At higher discharges, the total length of river stretches where dike raising would be necessary rapidly increases. Under conditions of the upper estimate for 2050 (i.e. design discharge equal to 17,000 m^3/s; figure 9.4) these alternatives can compensate the increasing discharge over only about 50% of the total river length; along the other 50% the current dike levels are exceeded by the design flood water levels. In the case when the rough target vegetation is preserved in the N alternative, flood water levels will exceed the dike levels over nearly 90% of the total dike length. For the projection year 2100, where more time is available for floodplain lowering and digging of side channels, the alternatives S and N can compensate over nearly 70% of the total river length for an increased design discharge equal to 17,000 m^3/s. In case of the extreme scenario where the design discharge rises to 18,000 m^3/s, these alternatives compensate water levels only over 40% of the river stretches.

Flexibility of alternatives

The flexibility of the alternatives might be assessed by considering to what extent they can maintain their, while implementing flood reduction measures. Up to what design discharge does each of the alternatives allow to implement additional flood reduction measures without either losing its typical characteristics (such as river forests, preservation of culture landscape) or demanding large-scale dike raising? Here an arbitrary criterion was used that an alternative must be able to ensure safe dikes over 70% of the total river length. It again must be noted here that these results depend on our choice of allowable measures within each alternative.

Alternative S appears to be the most flexible. In the projection year 2050 a design discharge equal to 16,500 m^3/s can be handled without exceeding water levels over 70% of the total length of river dikes, while preserving current land use. For the projection year 2100, this can be said up to discharges of 17,000 m^3/s. Alternative N(2) enables compensation of water levels for design discharges up to 16,250 m^3/s. If the design discharge further increases, the hydraulic roughness of the target vegetation (river forests) becomes a major limitation. In alternative N(1), the current target vegetation was replaced by a hydraulically more smooth vegetation type, resulting in longer river stretches where the safety levels are maintained. However, the original character of this alternative, the target vegetation according to Postma et al. (1996), is then denied. For the LNC alternative the dilemma rises between conservation of landscape versus flood reductions measures. Leaving all valuable areas unaffected would seriously reduce safety and thus demands additional flood reduction measures.



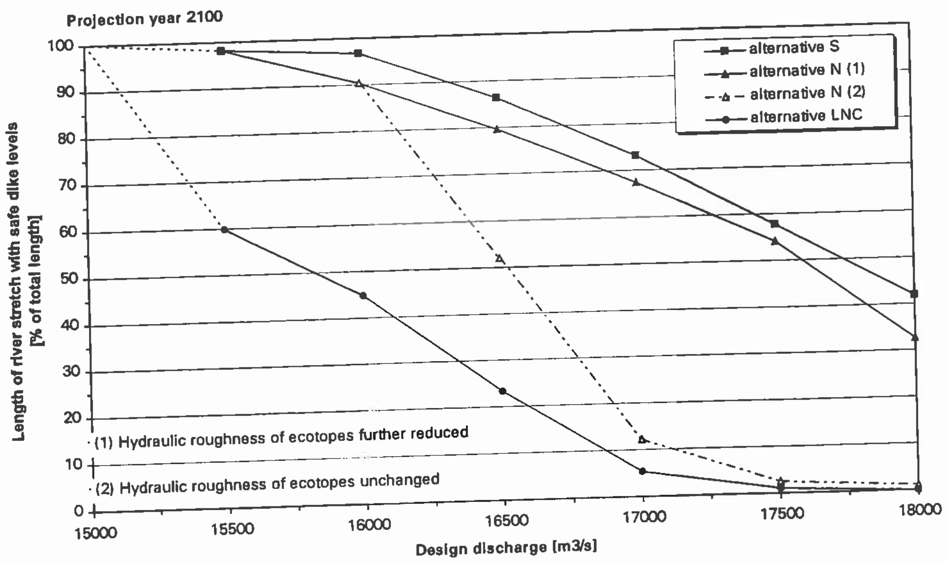


Figure 9.4 Total length of river stretches where current safety levels can be maintained at increasing design discharge for different landscaping alternatives. Top: projection year 2050; Bottom: projection year 2100.

Temporal development

To evaluate the flood reduction effects of the landscaping alternatives in time, the lengths of 'safe' dike stretches are indicated for all scenarios against the projection years 2050 and 2100. The example for the alternative Safety with current land use (figure 9.5) shows the decrease of the length of 'safe' dike sections in 2050. Nevertheless, a remarkable rise of the river lengths over which increased flood water levels can be compensated occurs between the projection years 2050 and 2100. Under the constraints assumed in the present study, the time until the year 2050 is relatively short to fully use the measure floodplain lowering for reducing flood water levels. Up to the year 2100 this time constraint is no longer limiting, allowing the full application of this measure. The same holds for digging secondary channels and for dike repositioning.

The decrease of the 'unsafe' length of dike sections that follows the initial increase of this length is an undesired situation. Suppose that at those dike sections for which landscaping alternatives cannot adequately reduce the flood water levels, the river dikes are raised. After the year 2050, however, it appears that additional measures have become effective, so that dike rising would no longer needed in all sections that previously were adapted. Those raised dike sections would on the one hand give some 'extra' safety, but on the other hand, they must be regarded as a 'regretful' measure. Landscaping plans and regulations around these therefore should always aim at minimising such 'regret' situations.

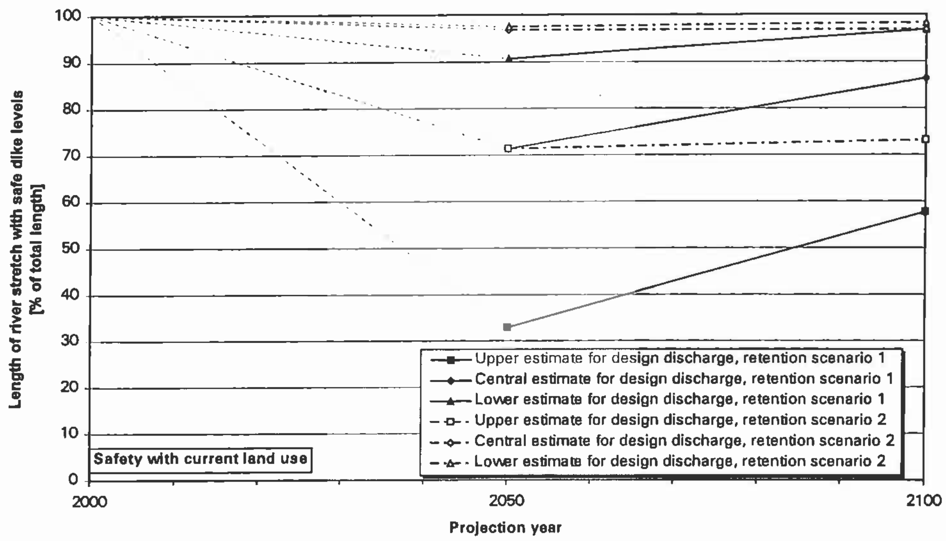


Figure 9.5 Total length where current safety level is maintained at the time horizons 2050 and 2100 for different climate and retention scenarios - Alternative: Safety with current land use
Up: alternative S; Middle: alternative N; Bottom: alternative LNC

9.4 Cost effects

The cost of each alternative can be subdivided into the cost of the implementation and the subsequent maintenance (in particular of nature areas). The implementation cost include the cost of all measures taken, the sanitation cost of polluted overbank sediments, plus the cost of dike enforcement of remaining unsafe dike sections. The cost of dike raising of less than 0.1 m is not considered. In general, the implementation cost of alternative S is the lowest. Alternative N has the highest cost for moderate increases of peak flows, whilst alternative N+L is the most costly in case of large increases of peak flows. The maintenance cost for nature is highest in the N alternative. The landscaping alternative N+L leads to the longest river section where water levels exceed the dike crest levels and also to the largest increases of design water levels; about 2 to 3 times as high as for the other alternatives.

For the projection year 2050 the extra cost demanded for additional water level compensating measures needed if climate changes are in the order of 200 million guilders for the alternative S, 100 million guilders for alternative N and 300 for alternative LNC. For the projection year 2100 the extra cost are 500 million guilders for the alternative S, 200 million guilders for alternative N and 500 for alternative LNC. The cost does not include measures taken in the Rhine basin upstream of Lobith, nor the implementation of retention within the Netherlands.

9.5 Effects for other functions

Nature

The effects for nature are expressed by the areas of natural ecotopes, the percentages of forested area and the length of natural riverbanks. Though for the N alternative these nature indices are highest under present-day conditions, the implementation of the target situation for ecotopes as defined by Postma et al. (1995) becomes seriously limited when the design discharge increases to 17000 m^3/s and higher. In general, for all alternatives, including the N alternative, the development of river forests will become seriously limited. This may imply that in the case the design discharge indeed exceeds 16,500 or 17000 m^3/s, the current vision on the target nature type as described by Postma et al. (1996), which includes large areas of hydraulic rough vegetation and river forests, needs to be reconsidered. An alternative may be a more wetland vegetation type that is found on low floodplain areas.

Agriculture

The landscaping alternative 'Safety with current land use' by definition aims at preserving the current surface area for agriculture. Also, the 'Nature plus Landscape' (LNC) alternative leaves large areas of agriculture land unaffected, since these are part of the culture landscape. In contrast, the Nature development alternative (N) causes a complete disappearance of agriculture from the floodplain area. Obviously, in the cases analysed in this study, the area available for agriculture is mainly determined by the landscaping alternative adopted and not by increasing river discharges.

Recreation

Nature-bound recreation will benefit from the measures carried out under landscaping alternative N, and to a smaller extent, under alternative LNC. With the definition of recreation areas used in the present study (cf. Silva & Kok, 1996) the total area for recreation is not sensitive to an increase of the design discharge, but only depends on the landscaping alternative.

Preservation of valuable culture landscapes

The smallest overall-loss of valuable culture landscape was obtained when leaving the IJssel floodplains unaffected, and sacrificing the Waal floodplain for enlarging the total discharge capacity of the lower Rhine branches. This led, however, to an unequal distribution of affected areas along Waal and Nederrijn and preservation along the IJssel. When comparing the effects of the alternatives 'Nature development' (N) and 'Nature plus culture landscape' (LNC), the first one results in a ten times larger area where culture landscape is affected.

9.6 Conclusions

Climate-induced increases of peak flows are expected to increase constraints to the spatial extent of the user functions of the high-water bed of the lower Rhine. Depending on the priorities given to different functions and depending on our 'visions' about the future landscape of the rivers, different ways of 'making way for the rivers' can be developed. The concept of the landscaping alternatives introduced by Silva & Kok (1996) provided for the present study a base for a first assessment of the implications for the user functions. The results obtained here largely depend on the assumptions made concerning the future effects of retention, the implementation rate of measures, the concepts behind the considered landscaping alternatives and priorities of measures. Nevertheless, the results provide valuable insight in opportunities provided by different landscaping visions, and the potential consequences of climate change on safety, agriculture, nature, culture landscapes and recreation.

Implications for landscaping alternatives

The alternative 'Safety with current land use' (S) offers most opportunities for creating more room for the river. The same is true for the alternative 'nature development' (N), provided the original target nature types (with large areas of forest) are replaced by a vegetation type that occurs on low floodplains and with a lower hydraulic roughness. The alternative 'Nature plus landscape' (LNC) that aim at preservation of valuable culture landscapes offers very limited possibilities for enlarging the high-water bed of the rivers. Implications of climate changes in terms of budget cost can only be made in general and qualitative terms. For the cases considered here, the total extra cost due to climate change are in the order of 100 to 300 million guilders until 2050 and in the order of 200 to 500 million guilders until 2100.

Implications for river functions

In case the net design discharge (i.e. climate induced rise minus the effects of upstream retention) does not exceed about 16,500 m^3/s in the next 50 years (which is according to the lower and central estimates), landscaping measures within the high-water bed according to the variants 'Safety with current land use' (S) and 'Nature development' (N) will largely be adequate in compensating for higher water levels. However, the alternative 'Nature plus culture landscape' (NLC) offers limited possibilities for maintaining safety levels without dike rising. Considering the projection year 2100, even the most effective alternatives cannot prevent an increasing reduction of the length of safe river stretches for the central and upper estimates of climate change.

The implementation of the target situation for ecotopes with river forests as defined by Postma et al. (1995) becomes seriously limited when the design discharge increases to 17,000 m^3/s and higher. This may imply that in the case the design discharge indeed exceeds 16,500 - 17,000 m^3/s, the current vision on the target nature type needs to be reconsidered. An alternative may be a more wetland vegetation type that is found on low floodplain areas.

The most efficient measures for lowering water levels (floodplain lowering, dike displacement, removing minor embankments) severely affect the present culture landscape of the floodplain areas. Where safety and nature relatively easily can negotiate win-win deals in choosing landscaping measures, the culture landscape seems to be the loser in the inevitable case the high-water bed must be enlarged in response to a rising design discharge. This demands a conscious weighing of interests and cost as well as carefully designed local landscaping plans. The consequences for agriculture and recreation are mostly determined by the landscaping vision adopted, and not by climate.

General remarks

Considering the uncertainty on the rate and magnitude of the increase of the design discharge, a policy of no-regret with a time horizon of several decades should be followed in the design of landscaping alternatives and strategies for flood reduction measures. Several measures are very expensive, strongly affect the present landscape, are irreversible, and thus they should only be applied when necessary. Some measures demand a long period of preparation and implementation, and cannot be implemented immediately in response to new evidence or insights on changes in the design discharge. Therefore, costly flood protection measures should preferably improve serveral functions at the same time, such as nature development, and spatial reservations should already be taken now to allow preparation for further increasing design discharge.

In the extreme scenario, when the net design discharge would rise to such amounts as 18,000 m^3/s, landscaping measures within the high-water bed of the rivers alone cannot compensate for the increased water levels, unless all floodplain are entirely lowered by about 2 m. In such a situation alternative, more large-scale measures should be considered, such as:

- Increasing the capacity of upstream retention along the river, which is presently under consideration and partly being implemented within the framework of international flood protection measures along the Rhine.
- Adapting the water distribution over the three Rhine branches: for example, diverting all extra water through the largest branch, the Waal, will pose a much lower limitations for river forests, culturally valuable landscapes, and leads to lower cost of the measures.

10 Implications for inland navigation

Hans Middelkoop
Willem .P.A. van Deursen

10.1 Introduction

The Rhine is one of the main transport arteries linking the world port of Rotterdam to the Ruhr and central Europe as far as Basel. The water level in the Rhine is usually high enough to be navigable for freight vessels, some 170,000 of which pass Lobith every year. About 150 million tonnes of freight a year are carried over the Waal, Western Europe's busiest shipping river. Inland navigation is considered an economical and safe transport mode that is less harmful to the environment than other transport modes, such as road transport. In the next 25 years or so, the annual volume of freight traffic by inland navigation in the Netherlands is expected to rise to over 350 million tonnes. Over the forthcoming decennia, climate change is expected to cause more frequent and prolonged periods of low water in the late summer and autumn (Van Deursen, 1999). During the winter, on the other hand, the chances of extreme flood will be greater. Such variations in river flow could have implications for transport along the Rhine route between Rotterdam and Germany. In the summer, it is more likely that shippers will not be able to fully load their vessels; it is even possible that there will be times when the rivers become impassable for heavy commercial traffic. Shipping on the Meuse is less sensitive to low flows, since the river is largely rendered.

In the present study, the potential consequences of climate-induced changes in Rhine discharge for inland navigation have therefore been explored.

10.2 Methods

The potential consequences of climate change for inland navigation have been explored in several steps.

1. The changes in flow durations of extremely high and extremely low discharges in the Rhine at Lobith in response to different climate scenarios have been determined using the RHINEFLOW model. For the scenario discharge series, the changes in the frequency and annual lengths have been determined of periods during which ships cannot be fully loaded, or even cannot sail at all. Timmermans (1995) and Nomden (1996, 1997) have carried out this part of the study.
2. Using the PAWN model (NEA, 1995; Projectgroep Watersysteemverkenningen, 1996), the additional costs of transport by inland navigation for the main waterways within the Netherlands have been estimated for the three CPB scenarios.
3. More insight in the logistics and potential flexibility of different sectors of inland navigation has been acquired on the basis of previous studies (Van Geenhuizen et al., 1996; Frederick Harris, 1997). Also, the authors participated in a workshop in the potential impacts of climate change on inland navigation. During this workshop the awareness of climate change among the stakeholders was increased, and a first inventory of possible solutions was discussed.

4. A model, called SHIPS@RISK (Van Deursen, 1997) has been developed to simulate the transport of goods between Rotterdam and the German hinterland under varying conditions of water levels in the river on the one hand and for various ship types and numbers, loads to be transported, stock sizes etc. Using the model different scenarios were evaluated to explore the sensitivity of the sector to changed discharge conditions as well as the possibilities for adaptation to changing conditions. With the model several sessions were held with stakeholders (ship owner, operator and expeditor) in which scenario runs were carried out, the flexibility of the sector was explored, and possible measures were discussed.

10.3 Results

10.3.1 Rhineflow analyses

The model experiments using RHINEFLOW have demonstrated that climate change will increase the hydrological limitations for inland navigation, in the sense that situations with limited water availability resulting in a reduced navigation depth are expect to occur more frequently over the century to come (figures 10.1 and 10.2) (Timmermans, 1995; Nomden, 1997). Reduced water depth reduces the transporting capacity and may affect the reliability of the sector. Improvements of the water ways of the Waal and the Middle Rhine may only partly compensate for the reduction in river discharge, so the adverse effects of climate change may become sensible over the next decades. Climate change should thus be considered a realistic issue for inland navigation.

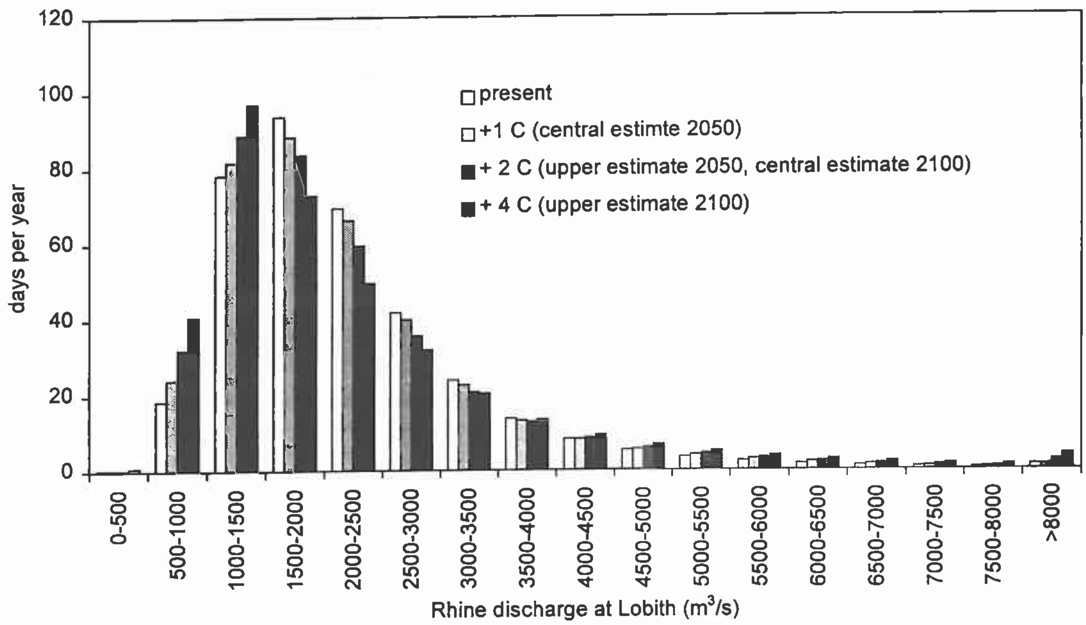


Figure 10.1 Frequency distributions of Rhine discharge at Lobith for different climate change scenarios

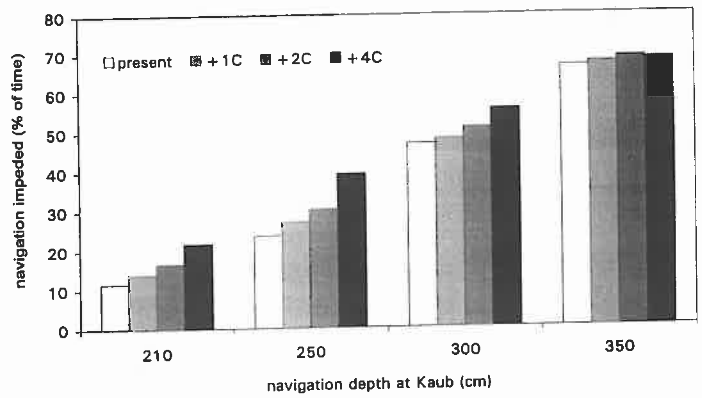


Figure 10.2 Percentage of time that navigation is impeded along the Rhine near Kaub for different navigation depth classes

10.3.2 Results of the PAWN model

In general, the socio-economic scenarios envisage an intensified traffic over the main waterways from Rotterdam to the German hinterland, and there is a tendency to using larger vessels. A major increase in the volume of transport by inland navigation by larger vessels, however, will increase the vulnerability to an increase in the frequency of situations with low water levels in the rivers, as well as traffic congestion near sluices and bottlenecks in canals. The model calculations indicated that climate change may lead to a rise of the cost of navigation by hundreds of millions guilders per year. In case of an economic development according to the GS scenario, the increase in annual cost is about one third of these figures in case of the ER scenario (table 10.1). When accounting for the changes in volumes of transport considered in the different CPB scenarios, the increases in transporting cost per ton are in the order of 8% for the ER scenario under the central estimate in 2050, and about 2% for the GS scenario. The calculations in this second step did not consider any adaptation by the sector to changing circumstances, for example by using different types of ships, lighter ships, or increasing storage capacities of stockyards. Therefore, these results must be regarded as a 'worst-case' situation. Nevertheless, they well demonstrate in a quantitative way that the sector is *sensitive* to climate change, and suggest that it may lead to a considerable increase in transporting cost.

Table 10.1 Increase in transporting cost due to climate change for the CPB European Renaissance and Global Shift scenarios

CPB-scenario	Climate scenario	Cost increase (Mfl per year)	Cost increase per ton (%)
ER	CEN2050	470	8
ER	UP2050, CEN2100	910	14
ER	UP2100	1450	22
GS	CEN2050	177	2
GS	UP2050, CEN2100	272	4
GS	UP2100	390	6

10.3.3 Perspective of the sector

Inventory studies carried out by Van Geenhuizen et al. (1996) and Fredric Harris (1997) and the literature review on the perspective of the sector on the issue of climate change demonstrated that the sector recognises Climate Change as a potential problem, as this affects both the transporting capacity and the transport reliability. Nevertheless, the sector does not envisage a change in modality (rail, road) due to climate change. Problems related to navigation restraints due to low water levels might be the most relevant impact of Climate Change for the inland-shipping sector. Continuity is considered the boundary condition for minimising logistic costs. Continuity is not guaranteed when navigation restraints last longer than a few weeks, depending on the load type. A solution for power stations and steel industries could be increase in storage capacity at the industry location. For chemical industries this increase in storage capacity would be too expensive.

An important part of the discussion was devoted to the question which party should take the lead in defining measures. Is the issue of impacts of climate change on the inland shipping sector entirely the responsibility of the inland shipping sector, or should the (international) water manager adjust the river system.
The inland shipping sector can (potentially) implement a number of measures to increase reliability

- Extra ships during low water periods
- Continuous operation instead of 8 hour operation during low water periods
- Closer cooperation with train and road transport

The implementation of modern specifications for the construction of barges may aim at constructing 'Lightweight' ships which have less draught for the same weight of cargo, and which are more economical with respect to fuel usage.

- Measures from the water management side should be considered as well, including:
- Further research into possible measures within the river system, such as adapting channel dimensions: the participants of the workshop emphasize the importance of draught over channel width.
- Water preservation in the upstream basin to increase the base flow during dry periods. Such measures should be analysed in the framework of a no-regret policy, measures for attenuation of the floods, management strategies for Swiss lakes and so forth.

10.3.4 Results of the SHIP@RISK sessions

As a final step, a model, called SHIPS@RISK has been developed to simulate the transport of goods between Rotterdam and the German hinterland under varying conditions of water levels in the river for various ship types and numbers, loads to be transported, stock sizes etc. Using the SHIPS@RISK model different scenarios were evaluated to explore the sensitivity of the sector to changed discharge conditions as well as the possibilities for adaptation to changing conditions (Mol & Van Deursen, 1998). With the model several sessions were held with stakeholders (ship owner, operator and expeditor) in which scenario runs were carried out, the flexibility of the sector was explored, and possible measures were discussed.

The case studies with the SHIPS@RISK model demonstrated that the inland navigation transport sector has to a certain degree a flexibility to cope with the variations in water levels that occur even under present-day conditions. This flexibility is implemented in the form of logistical (such as temporary storage of goods or using extra push-barges at times of low water), and economic (such as financial compensation for transport during periods of low water) measures. In general, the climate-induced hydrological changes will put an additional pressure on the current flexibility, and raises the need for increasing this flexibility. In view of the long time horizon of the expected changes, the inland shipping sector and the water manager can (potentially) implement a number of measures to mitigate the problems. These can be technical (e.g. developing lighter types of ships), logistic (adapting transporting schemes) or economic (insurance, price compensation) in nature.

10.4 Conclusions

The inventory studies clearly show that the physical boundary conditions for the inland shipping sector will change as a result of possible climate change. Periods of reduced water depth for navigation will occur more frequently and may last longer, while extremely high floods are expected to occur more frequently. These changes are unfavourable for the sector; under the assumption of an *inflexible* inland shipping sector the consequences of these hydrological changes are:

- The cargo capacity decreases due to decreased draught with decreased discharge.
- The transport reliability decreases due to increase in occurrence and/or duration of high water restraints.
- The hydrological changes caused by climate change will substantially increase transport costs by inland shipping in the case of an inflexible inland shipping sector.

These first inventories indicated that the sector is sensitive to the changing boundary conditions. The effects of climate change are not a-priori considered that serious that a structural change to other modalities (truck and train) is foreseen. The current trends towards larger vessels, however, increase the sensitivity for fluctuations in water level and climate. A complete disregarding of the potential problems might result in higher costs and increased problems.

The inland navigation transport sector has to a certain degree a flexibility to cope with the variations in water levels that occur even under present-day conditions. The issue is then to compare the hydrological changes resulting from the climate scenarios with the current flexibility of the sector. This flexibility is implemented in the form of logistic and economic measures. In general, the climate-induced hydrological changes will put an additional pressure on the current flexibility, and raises the need for increasing this flexibility.

In view of the long time horizon of the expected changes, the inland shipping sector and the water manager can (potentially) implement a number of measures to mitigate the problems. These can be technical (e.g. developing lighter types of ships), logistic (adapting transporting schemes) or economic (insurance, price compensations) in nature. This will reduce the vulnerability to extreme events and reduce the transportation cost.

Measures to mitigate problems that are envisaged under changing climate conditions may not necessarily be carried out only by the inland navigation sector. The river management sector may implement measures in improvement of waterways, such as currently being carried out in the Waal. Such measures should particularly aim at improving channel depth rather than widening the channel. More rigorous measures would aim at retaining and storing water in the upstream parts of the Rhine basin, in order to achieve a larger base flow during dry periods in summer. This latter category of measures can only be taken within the framework of integrated water management measure in the Rhine basin. It is interesting to notice that the desires from the side of inland navigation (i.e. avoiding discharge peaks, increasing river discharge during dry summer periods) are in line with the principles of flood mitigation and water conservation and retention as proposed for example by the IKSR (1995) within the framework of the flood protection action programme of the Rhine.

Finally, it is evident that climate change and the inherent uncertainties are not the only uncertainty this sector has to deal with. Compared to economic and other developments, climate change adds a moderate uncertainty in their future perspectives. This means that in a next step of a climate impact study the implications of climate change and a cost-benefit evaluation of proposed measures must be considered within in integrated framework of socio-economic and climate change perspectives.

11 Implications Rhine-Meuse estuary - a first evaluation

Hans Middelkoop

11.1 Introduction

This chapter summarises a series of inventory studies on the Rhine-Meuse estuary that considered climate change (sea level rise and changes in river flow) in combination with possible strategies for a new water management. The main sources of this section are Werkgroep klimaatverandering en Bodemdaling (1997); Hamels (1997), Gribnau & Ligthart (1998) and Snippen & Blom (1999). These studies have been carried out at RIZA-Dordrecht.

11.1.1 Description of the area and user functions

The watercourses and river branches of the Rhine-Meuse estuary are shown in figure 11.1. At the western side there is an open connection with the North Sea through the Nieuwe Waterweg. The southern part has been closed-off from the sea by the Haringvliet barrier since 1970 and a movable storm surge barrier has been present in the Nieuwe Waterweg since 1997. In the western part of the area the water levels are governed by the tides. Extreme water levels occur during storm surges. During high tide a wedge of salt water intrudes into the river mouths. During periods of low river flow this salt wedge sometimes reaches as far as into the Hollandsche IJssel (NE from Rotterdam to Gouda). In the eastern part, water flow and water levels are dominated by the discharge from the rivers Rhine (via the Lek and Waal) and Meuse. Here, extreme levels are the result of peak flows in the rivers. The influence of the Meuse discharge is substantially lower than that of the Rhine discharge.

The dynamics of water, salt and sediment fluxes within the area are determined by several factors: river discharge, tidal currents, wind offset, and manipulation with the sluice gates in the Haringvliet barrier. As long as the Rhine discharge at Lobith is lower than 1700 m^3/s, the sluices remain closed. When discharge becomes higher, the water fluxes are controlled in such as way that intrusion of salt water from the North Sea into the lower rivers is prevented. During periods of storm, the sluices remain closed.

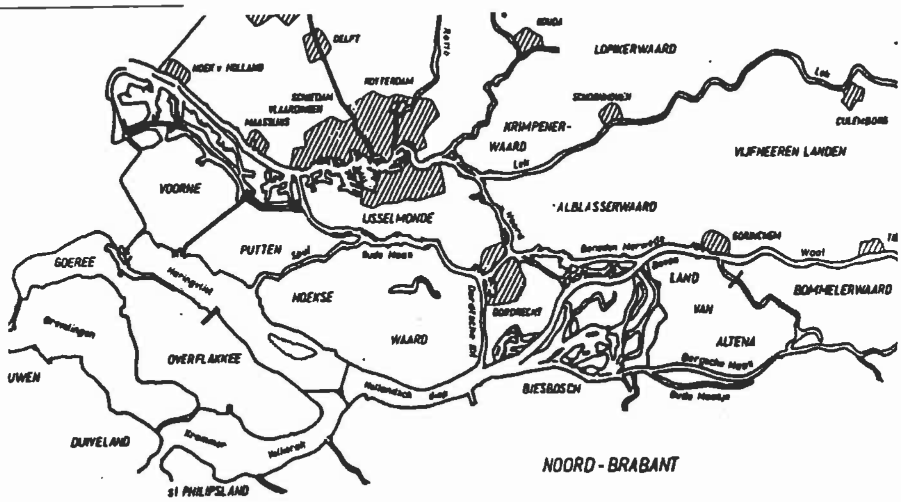


Figure 11.1 Rhine-Meuse Estuary

Safety

The safety standards of the dikes in this area vary along the watercourses. In the eastern part along the Biesbosch, Hollandsch Diep and lower Lek they are based on an annual probability of 1/2000, most of the embankments along the Haringvliet and Oude Maas on 1/4000, and the Rotterdam area and the northern side of the Nieuwe Waterweg on 1/10.000. The water levels corresponding to these standards depend on the tide, wind (storm frequency), and river discharge. During storm surges, the Haringvliet and Nieuwe Waterweg barriers are closed.

Nature and ecology

Before the enclosure the area was a natural estuary, with a diversity of salt water, brackish and fresh water areas, characterised by tidal flats, shoals and accretions, with the associated ecosystems. The tidal difference was about 2 m, and both the sea and the rivers carried sand and silt into the estuary. Due to the enclosure of the Haringvliet, the southern part of the Rhine-Meuse estuary has become a fresh-water basin, where salt intrusion hardly occurs; the boundary between salt and fresh water has become sharp. In the southern area, the natural tidal difference has been reduced to 0.2 to 0.3 m. The channel profiles that were in equilibrium with the tidal currents had become too wide and the southern part of the estuary has become a sedimentation basin. Particularly between 1970 and 1980, large amounts of polluted silts have been accumulated here. The estuary is the main port for fish to migrate upstream the rivers. However, the Haringvliet dam is an important barrier for fish migration.

Navigation

The waterways are characterised by an intensive navigation, particularly the Nieuwe Waterweg, and its connections to the hinterland, through the rivers Waal, Lek, and Meuse.

Water availability for agriculture, industry and domestic use

Fresh water from the lower river delta is used for agriculture (irrigation) and to flush the polders to prevent the seepage of brackish water from the sub-soil. In addition, there are several locations where the intake of fresh water takes place for industrial and domestic use. The salinity of the water taken may not be too high: a critical level equal to 215 mg/kg is presently the upper limit. During periods of very low river flow and high tide, the salinity of the water in the northern part of the estuary may temporarily exceed the critical level for water intake. At the station along the Hollandsche IJssel, water intake becomes limited when the Rhine discharge at Lobith drops below 1200 m^3/s.

11.1.2 Autonomous developments

As a result of the increasing awareness of the need for ecological restoration, alternative management programmes, comprising different strategies of partially re-opening the sluices in the barrier have recently been developed (Bol, 1993; Rijkswaterstaat, 1994; Koeze, 1995). These programmes should enable a recovery of the estuarine nature, including complete and balanced population of ecosystems, and sustainable utilisation of the water system on both sides of the Haringvliet barrier (Vanhemelrijk & De Hoog, 1996). Protection against flooding, however, remains the primary function of the dam. The proposed variants are the following:

- ZERO-variant: present management programme, encoded LPH84.
- BROKEN TIDE (previously encoded: HV2min): minor increase of the tide (up to 0.4 m), resulting in a partial recovery of the inter-tidal zone and shores.
- TAMED TIDE (previously encoded: ECO): sluices will be almost permanently opened, though with a limited capacity. The sluices are closed only for safety reasons or in case of very low river discharge (preventing salt intrusion). The tidal difference will be about 60 to 70 cm, which is still less than under natural conditions.
- STORM SURGE BARRIER, encoded SVK: the sluices will close during storm surges and will remain be opened to their full capacity otherwise.

These alternatives thus all aim at increasing the tidal dynamics in the basin and at achieving a more natural gradient in salinity. The effects of the alternative sluice programmes on salinity, morphological changes, and changes in water levels within the basin, as well as the effect on the user functions of the area are presently being evaluated in a Landscape Planning (IVB) study (e.g. Snippen & Blom, 1999). The results presented in this study have been partly carried out as a first exploration of the sensitivity of the area to different sluice management strategies in combination with climate change.

11.2 Methods

The consequences of climate change for the estuary have been evaluated in a sensitivity analysis for different sluice management alternatives. Extensive descriptions of these analyses are given in e.g. Hamels (1997), Gribnau & Ligthart (1998) and Snippen & Blom (1999). These studies mainly focused at water levels (extremes, tidal difference) and salinity.

To investigate the effects of changes in sea level, river discharge and water release through the Haringvliet Barrier on water levels and salinity, a one-dimensional hydrodynamic model, ZWENDL, was used. In the ZWENDL model the watercourses are represented as a network, in which each stretch is subdivided in sections of about 5 km length. Water flow and salt concentrations are calculated using equations of mass balance and of convective and diffusive motion, using a time step of 30 minutes to allow simulation of the tidal water movements. Boundary conditions are sea water level, tide and chloride concentration at the western border of the area, and river discharge of the lower Rhine and Meuse distributaries and their chloride concentrations at the upstream border. The model calculates at each section water level, flow velocity, discharge and chloride concentration. Chloride concentrations in the Rhine branches were about 200 mg/l, those in the North

Sea 15,000 mg/l. Details on the methods can be found in Snippen & Blom (1999) and Gribnau and Ligthart (1999).

Climate-induced changes in hydrological boundary conditions were applied as follows. On the basis of the RHINEFLOW model results, the frequencies of occurrences of high and low river discharges were determined for different climate scenarios. Changes in Meuse discharge were estimated on the basis of results obtained by Van Deursen (1999) (tables 11.2. and 11.2). In addition, average sea level was increased in three steps. For the estimation of changes in extreme water levels, 54 combinations of (9) river discharges and (6) storm set-up situations at sea were calculated over the entire tidal cycle for each scenario.

Model calculations were carried out for different situations with constant river discharge. Situations with high river discharge were evaluated to estimate the effect on design water levels, situations with low river discharge were evaluated to study possible salinity problems. The implications for salinity have been determined for two water intake stations for agriculture in the area: the Bernisse, located south of Rotterdam, and the station along the Hollandsche IJssel. This was done in a sensitivity analysis for the present situation (ZERO variant) and for the ECO and SVK variants of the Haringvliet sluice programmes, to which a sea level rise of 20, 60 and 85 cm was applied. In this first assessment, no long-term effects of autonomous adaptations of the channel dimensions and other geomorphological effects were considered.

Table 11.1 Number of days per year that the Rhine discharge at Lobith is below a critical discharge

Critical Rhine discharge (m^3/s)	Present (days per year)	CEN2050 (days per year)	UP2050, CEN2100 (days per year)	UP2100 (days per year)
800	7	9	13	18
1.000	25	30	40	50
1.200	50	60	75	90
1.700	145	150	165	180
2.200	230	230	240	240

Table 11.2 Scenarios for the estimation of changes in extreme water levels in the year 2050

Scenario	Sea level rise (cm)	Increase of peak discharge (>10,000 m^3/s) in the lower Rhine branches (%)	Increase of peak discharge (>2,000 m^3/s) in the lower Meuse (%)
Central estimate 2050	25	5%	10%
Upper estimate 2050	45	10%	20%

11.3 Results

11.3.1 Effects on extreme water levels and implications for safety

Model simulation concerning extremely high water levels were calculated for the current discharge programme of the Haringvliet barrier (ZERO variant). Table 11.3 summarises the estimated increases in design water levels, resulting from the first model calculations for the assumed climate change situations. In general the results indicate that:

- Water levels in the Haringvliet and Hollandsch Diep may increase about proportionally to average sea level;
- The influence of sea level reduces in the upstream direction;

- The effects on desing water levels in the northern part of the estuary (Nieuwe Waterweg) are smaller, as a result of the storm surge barriers in this area.

It must be noted, however, that these estimates are first model calculations that did not consider flood reduction measures. Further modelling experiments are still to be carried out for the other sluice management programmes. The results for the other sluice programmes, however, may be not very different from those persented here, since the barrier will be closed during periods of extreme sea water levels in all sluice programmes. Estimates given in Hamels (1997) indicate that under the SVK programme for the Haringvliet Barrier (which is the most extreme variant) the design water levels may be 5 cm higher for the Central estimate and 10 cm higher under the Upper estimate in 2050, when compared with the scenario results for the ZERO variant.

Table 11.3 Estimated increase in design water levels for the investigated climate change scenarios, projected to the year 2050 (ZERO variant). No additional water management measures assumed

Water course	Central estimate	Upper estimate
Lek	0.11	0.25
Haringvliet	0.25	0.45
Hollandsch Diep	0.25	0.45
Waal	0.25	0.50
Boven Merwede	0.25	0.45
Nieuwe Merwede	0.25	0.45
Beneden Merwede	0.20	0.40
Nieuwe Waterweg	0.10	0.20

11.3.2 Salinity and implications for water intake

Bernisse

Under conditions of the ZERO variant for the Haringvloet sluices, sea level rise does not lead to a limitation for the intake of water for agriculture from the Bernisse station (table 11.4). The ECO variant, however, already leads to a considerable limitation of the intake of water when the Rhine discharge drops below 17,000 m^3/s, even without climate change. The chloride concentrations under this variant are highly sensitive to a rise in sea level. Since the SVK variant leads to an increased flow of fresh water through the southern part of the estuary, this variant does not lead to limitations for the Bernisse station.

Hollandsche IJssel

Already under present-day conditions (ZERO variant), water intake becomes limited at low Rhine discharge. This becomes worse for discharge below 17,000 m^3/s if sea level rises. The ECO variant considerably limits the possibilities for water intake already with present-day sea level and river flow. Water intake becomes drastically limited when sea level rises, even at times of average Rhine flow. The results obtained for the SVK variant are similar to those for the ECO variant, though chloride concentrations are slightly lower.

For both intake stations it must be noted that in response to climate change, situations of low river flow are expected to occur more frequently. Thus, in addition to the reduction of the period per day that water intake can occur, there are fewer days per year at which chloride concentrations are low enough for taking water for agriculture. Conversely, long-term geomorphological developments may reduce the intrusion of the salt wedge. This will happen if sea level rise in combination with increased suspended sediment load from the rivers cause an accelerated sedimentation in the Haringvliet and Hollandsch Diep, which results in a rise of the bottom of these waters. Since the salt wedge mainly intrudes along the deepest parts of the water, the rise of the bottom prohibits part of the wedge to intrude.

Table 11.4 Percentages of the time per day during which chloride concentrations are sufficiently low for water intake from the stations Bernisse and Hollandsche IJssel

Variant and Q-Rhine (m^3/s)	Present (%)	SLR = 20 cm (%)	SLR = 60 cm (%)	SLR = 85 cm (%)
Bernisse - ZERO				
1,000	100	100	100	100
1,200	100	100	100	100
1,700	100	100	100	100
2,200	100	100	100	100
Bernisse - ECO				
1,000	0	0	0	0
1,200	35	0	0	0
1,700	80	60	50	40
2,200	90	90	75	60
Holl. IJssel - ZERO				
1,000	85	55	25	0
1,200	100	100	65	55
1,700	100	100	100	100
2,200	100	100	100	100
Holl. IJssel - ECO				
1,000	0	0	0	0
1,200	0	0	0	0
1,700	40	40	15	0
2,200	80	70	65	60

SLR = Sea Level Rise

11.4 Conclusions

The effect of applying alternative sluice programmes for the discharge sluices in the Haringvliet barrier seems larger than the effects of climate-induced sea level rise and changes in river discharge. The sluice management alternatives aim at improving the ecological conditions of the estuary, but make the other functions of the area more sensitive to climate change:

- Sea level rise in combination with an increase of extreme river flow will lead to an increase in the design water levels, particularly in the central and southern parts of the former estuary. Under conditions of the central estimate for 2050 design water levels may increase by about 25 cm.
- The more natural salinity gradient into the estuary that is aimed at by the investigated sluice variants will reduce the possibilities for freshwater intake for agriculture, particularly along the Hollandsche IJssel. This becomes drastically limited if climate change, even under moderate scenario conditions.
- Therefore, in the evaluation study for the Haringvliet (MER Haringvliet) the effects of the alternative sluice programmes should be well considered, both for the present-day situation and under conditions of changed climate.
- Prevention of extremely high water levels due to storm surges can to a certain extent be obtained using the storm surge barriers. However, climate change will lead to an increase of design water levels. Creating larger discharge and storage capacity of water within the high-water bed will

have little effect, as the volume of water coming from the sea is virtually unlimited. Conversely, narrowing the lowest sections of the estuary may reduce the influence of storm surges on the extreme water levels in the upstream sections.

- Depending on the adopted variant and climate change, the salinity may become systematically too high for agriculture. This will particularly occur during dry periods, when the demand for water is high. In those cases the intake point for water should be moved in the upstream direction. However, the intrusion of a salt wedge may be reduced if the floor of the Haringvliet and Hollandsch Diep rise due to accelerated sedimentation.
- The morphological response of the system to different sluice programmes in combination with sea level rise and changes in discharge and suspended sediment load from the rivers should be further analysed in future research.

12 The impact of climate change on the IJsselmeer Area

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12.1 Introduction

12.1.1 Description of the IJsselmeer area

The IJsselmeer area consist of the lakes IJsselmeer, Markermeer and the so-called Borderlakes (Wolderwijd/Nuldernauw and Veluwemeer/Drontermeer) (figure 12.1). Together, these form an interconnected system of six water compartments, so-called 'boezems'. The IJsselmeer has been separated since 1932 from the Wadden Sea by a barrier, the Afsluitdijk. It is presently the largest fresh water lake in the Netherlands, with an area of about 1200 km^2 and an average depth of 4.4 m. The dimensions of the lakes in the IJsselmeer area are summarised in table 12.1.

Table 12.1 Area, average depth, border length and retention time of water in the lakes (NAP = Dutch Ordnance Datum)

	Area (km^2)	Average depth (m -NAP)	Border length (km)	Average retention time summer (months)	winter (months)
IJsselmeer	1182	4.4	433	5	3
Markermeer	733	3.5	347	12	15
Veluwemeer/ Drontermeer	37	1.4	99	3	2
Wolderwijd/ Nuldernauw	25	1.8	62	9	5

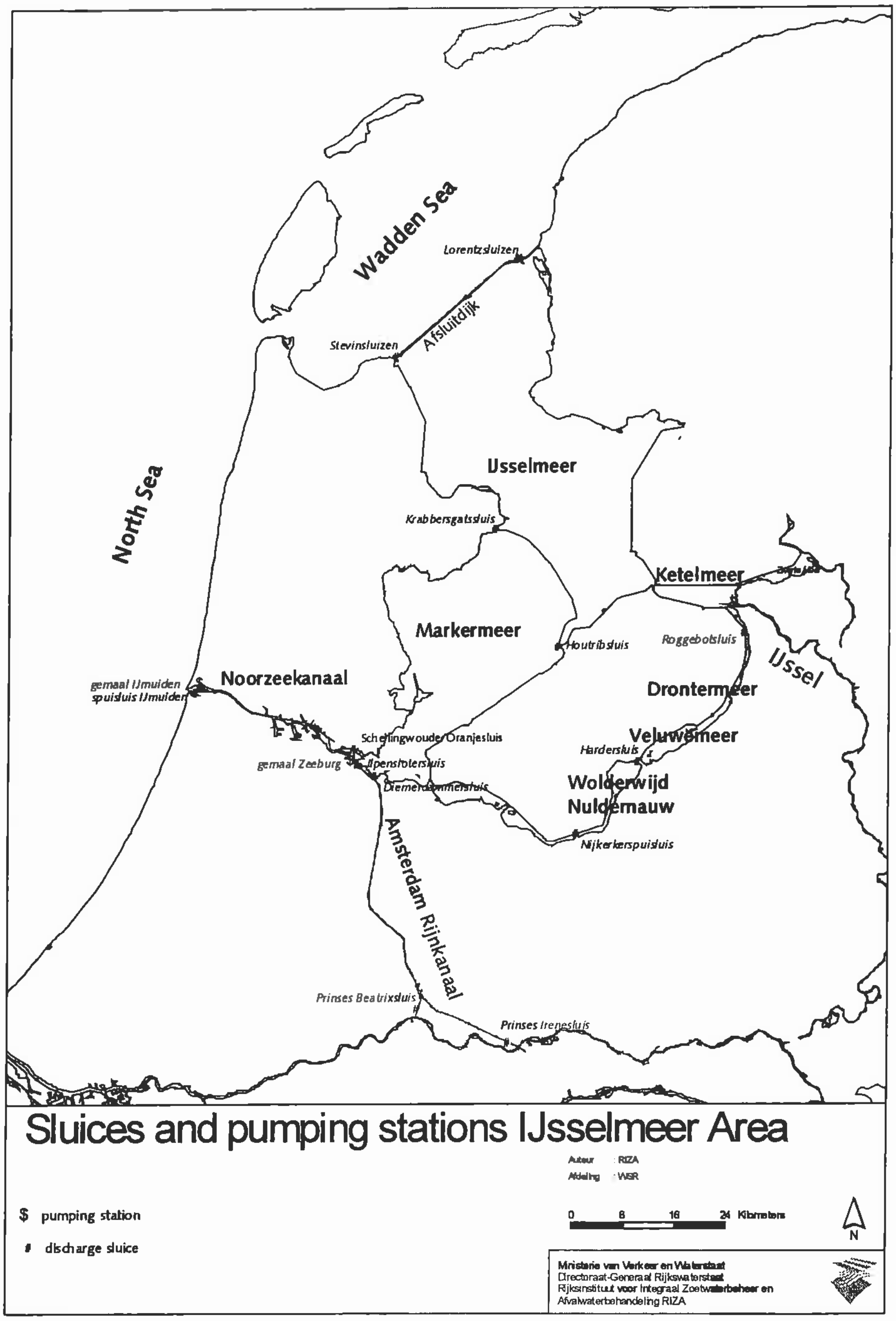

Figure 12.1 IJsselmeer area with discharge sluices and pumping station that discharge water to the area

12.1.2 Functions of the IJsselmeer area

Being a large freshwater basin, the IJsselmeer area has a number of socio-economic and ecological functions. Most functions depend on the lake level (cf. Iedema & Breukers, 1998).

Safety
The safety standards of the dikes bordering the IJsselmeer area are based on annual failure probabilities varying between 1/10,000 (western part) and 1/1250 (eastern parts). The requested dimensions of the dikes not only depend on the lake levels, but they are also determined by wind set-up of water levels, and wave action against the dikes.

Water supply for agriculture, industry and drinking water
Water from the IJsselmeer and Markermeer is used for agriculture, for maintaining groundwater levels during dry periods, and for flushing the surrounding areas to prevent salt intrusion. During winter, the water surplus from the polders is pumped into the IJsselmeer. If this excess water cannot be adequately released, water levels of the local water storage canals ('boezems') within the polders may exceed critical levels. Particularly in the Noordzeekanaal, problems of discharging excess water from the surrounding polders may arise during extremely wet periods. In most summers, the demands for water supply to the polders can be easily fulfilled. However, during dry summer periods the demand is nearly as high as the total water availability from the IJsselmeer. Several power stations within the area use surface water for cooling. Annually, 74 million m^3 water is taken from the IJsselmeer to be used as drinking water for 1.2 million people. Salinity of the water is important and the concentration chloride may not exceed 200 mg/l, but should be below 100 mg Cl/l.

Inland navigation
The IJsselmeer and the Markermeer are important links in the inland network of waterways. Within the IJsselmeer several navigation fairways have been dug. Infrastructure works have been designed on the basis of the present lake levels. A reduction of water levels may cause problems for passing locks; higher water levels are not considered to rise problems for navigation.

Nature
After the enclosure of the former Zuiderzee, the IJsselmeer has turned into a fresh to brackish water basin. The area is of great importance for nature, in particular for bird life. However, the current lake level management, with low winter levels, and high summer levels, is opposite to natural fluctuations. Natural transitions in vegetation from land to water hardly occur along the lake's borders. The Afsluitdijk has also resulted in an unnatural sharp transition from brackish to fresh water. In view of ecological improvements, the Directorate IJsselmeer Area has drawn up a number of objectives for nature development in this area (cf. Iedema & Breukers, 1998).

Recreation
The IJsselmeer area is extensively used for recreation such as, sailing, fishing, bathing etc. The conditions for recreation depend on temperature (air and water), lake level (beach width) and water quality. Algae bloom and botulism, which may occur during warm periods, are unfavourable conditions.

12.1.3 Water management of the IJsselmeer area

The lake levels result from the water balance that is controlled by the influx of water via the IJssel (a distributary of the River Rhine), and the release of water into the Wadden Sea through outlet sluices in the Afsluitdijk. The IJssel carries about 15 percent of the annual Rhine discharge into the IJsselmeer (on the average 390 m^3/s). In addition, water is discharged into the lake by the Overijsselse Vecht (64 m^3/s), a small lowland river, and from polders (40 m^3/s) around the lake. The contribution from direct rainfall is equivalent to an annual influx rate of about 30 m^3/s. The water surplus is discharged through 25 sluices in the Afsluitdijk (490 m^3/s). Although less important, intake by polders (20 m^3/s) and evaporation (equivalent to 25 m^3/s) are the main other loss factors. Table 12.2 shows the relative contributions to the water balance of different components of the IJsselmeer area for the summer and winter season.

Table 12.2 Relative contribution of water fluxes to the water balance of the IJsselmeer area

	IJsselmeer		Markermeer		Veluwemeer		Wolderwijd	
	summer	winter	summer	winter	summer	winter	summer	winter
Flow rate into lake (%)								
Precipitation	6	6	15	30	14	8	31	19
River discharge	87	79	8	25	24	26	12	25
Pumped from surrounding area	5	9	8	27	50	58	10	10
Discharged from surrounding area	2	7	69	18	1	0	32	35
Groundwater seepage	0	0	0	0	11	7	15	10
Flow rate from lake (%)								
Evaporation	8	1	27	9	16	2	40	4
Water supply	8	1	33	18	0	0	1	0
Discharge to surrounding area\Wadden Sea	84	98	40	73	31	69	41	86
Downward seepage	0	0	0	0	53	30	18	10
Total discharge out								
m^3/s	474	674	90	70	8	13	2	4
mm	34	49	10	8	19	31	6	13

Discharging water from the IJsselmeer through the sluices in the Afsluitdijk into the Wadden Sea takes place by gravity during low tide only. During high tide and under bad weather conditions, sea water level exceeds the IJsselmeer level and the sluice gates remain closed. Due to wind set-up (NW-wind direction), free discharge may be temporarily obstructed even at low tide. For those situations, the capacity of the IJsselmeer should be sufficiently large to store the excess water until weather conditions allow the water release to the Wadden Sea again. The control of the water balances between the 'boezems' is carried out using discharge sluices. In summer, the Markermeer is flushed with water from the IJsselmeer to reduce salinity. The water from the Markermeer is then released into the Noordzeekanaal, which in turn discharges into the North Sea through discharge sluices and by a pumping station.

Water management in the IJsselmeer is based on the so-called 'target' water levels (table 12.3). The target lake levels in the IJsselmeer and Markermeer are -0.40 m NAP (NAP = Dutch Ordnance Datum) in winter, to achieve a sufficiently large storage capacity for excess water from the IJssel during periods of high river discharge, without risking too high water levels. During summer, a higher target level (-0.20 m NAP) is maintained to achieve a larger volume of fresh water stored in the lake. Since extremely high lake levels (e.g. due to peak flows of the River IJssel) do not occur during summer, this higher level has no adverse effects on safety. The summer target levels can be well maintained. During winter, however, the lake levels systematically exceed the target level, because the discharge capacity of the sluices in the Afsluitdijk is lower than the average total discharge into the lake.

Table 12.3 Target and measured lake levels (1976 - 1993) relative to NAP (a minus sign means below NAP)

	winter				summer			
	target	average	maximum	minimum	target	average	maximum	minimum
IJsselmeer	-0.40	-0.27	0.34	-0.51	-0.20	-0.17	0.08	-0.31
Markermeer	-0.40	-0.32	0.07	-0.43	-0.20	-0.19	-0.05	-0.33
Veluwemeer	-0.30	-0.19	0.29	-0.49	-0.05	-0.07	0.18	-0.23
Wolderwijd	-0.30	-0.24	0.05	-0.39	-0.10	-0.12	0.06	-0.25

12.2 Methods

The effects of climate change on the IJsselmeer area are calculated using models of the so-called WINBOS instrument (version 1.0). WINBOS is a decision support system that consists of several coupled models, developed for the WIN-study (Water Management in the central part of the Netherlands (Iedema & Breukers, 1998; Oosterberg et al., 1998) to study the effects of alternative water management strategies and changing climate on the IJsselmeer Area. Using the water balance model BekkenWIN (Buiteveld et al., 1999), the lake levels and the discharges through sluices and pumping stations were calculated for different scenarios. The effects of climate change on the safety against flooding around the IJsselmeer area have been determined with the module HydraWin (Fokkink, 1998) that calculates the design crest levels of the dikes around the IJsselmeer and Markermeer from the lake levels and wind statistics. An important assumption in all scenarios is the assumption of an unchanged wind regime. The modules for regional drainage and supply calculated whether the present infrastructure is adequate to fulfil the water demands. The salt concentration was calculated using the model ZoutMeren.

BekkenWin

The water balance model BekkenWin is the central module of WINBOS for hydrology and hydraulic calculations. The model BekkenWin is made using SOBEK. The first version of this model was developed in 1997 (Fokkink, 1997). Modifications and updates of this first version were made in order to use the model for the present NRP-study and the WIN-study (Fokkink & Van Ellen, 1997; Fokkink, 1998; Buiteveld et al., 1999). BekkenWin simulates the water balances for the water compartments IJsselmeer, Markermeer, Noordzeekanaal/Amsterdam-Rijnkanaal, Randmeren. In BekkenWin the lakes Wolderwijd, Nuldernauw, Veluwemeer and Nuldernauw are considered one compartment, called Randmeren. The Hardersluis is removed, in accordance with the situation planned for the year 2000. BekkenWin calculates the mean water levels in the compartments, the discharges through all structures and the monthly residence times of water for all compartments. The calculation time step is 30 minutes and the output of the model is a time series of daily mean values of lake levels and discharges. The output of BekkenWin is used for the other WIN modules.

Figure 12.2 shows examples of the calculated water levels. The model results are in accordance with the measured mean winter and summer levels, and the minimum water levels. The computed average, maximum and minimum water levels per season are presented in table 12.4, together with the measured levels. The measured series comprises the period 1983-1996; the model results have been generated for the same period.

Figure 12.3 gives the discharge from the Noordzeekanaal to the North Sea for the pumping station and the discharge sluice. These discharges are in good agreement with the measured discharges. The differences can be attributed to changes in the water management in time, which have not been considered by BekkenWin. The measurements of the period 1990-1992 were used for model calibration.

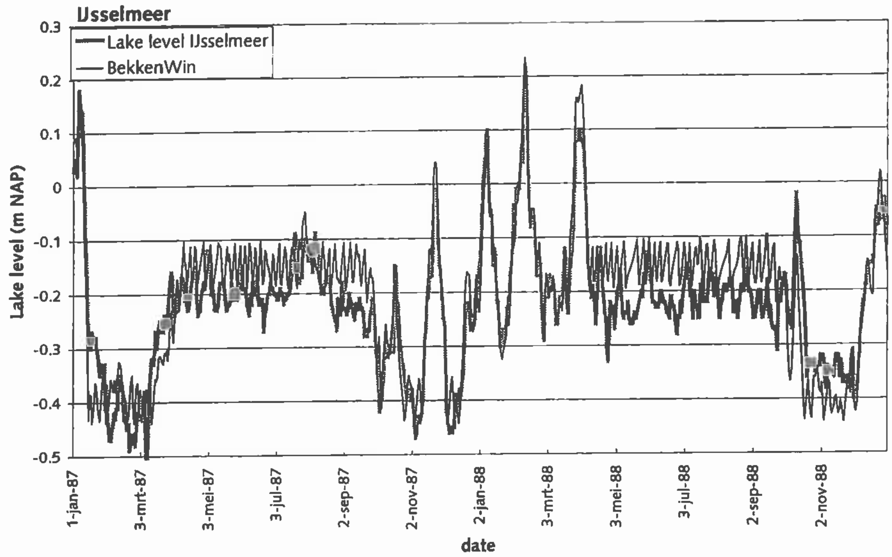

Figure 12.2 Measured and calculated (BekkenWin) lake levels IJsselmeer

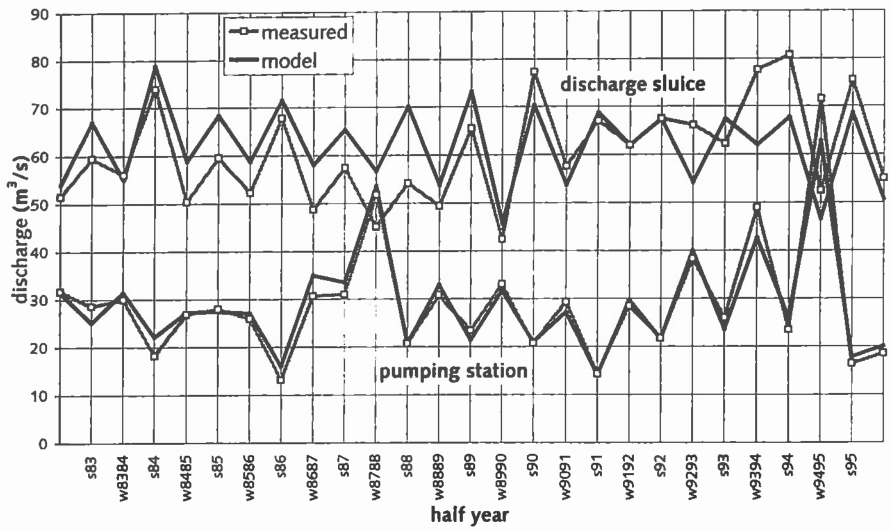

Figure 12.3 Summer and winter mean discharge from the Noordzeekanaal to the North Sea for the pumping station and the discharge sluice near IJmuiden. The model results are calculated with BekkenWin

Table 12.4 Measured and calculated (BekkenWin) water levels of period 1983-1995 (m +NAP) (Buiteveld et al., 1999)

	average winter (m)	average summer (m)	maximum (m)	minimum (m)
Measured				
IJsselmeer	-0.26	-0.17	0.34	-0.51
Markermeer	-0.31	-0.18	0.19	-0.45
Noordzeekanaal	-0.41	-0.40	-0.19	-0.52
BekkenWin				
IJsselmeer	-0.29	-0.15	0.32	-0.45
Markermeer	-0.31	-0.17	0.12	-0.43
Noordzeekanaal	-0.41	-0.41	-0.21	-0.47

12.3 Results

12.3.1 Hydrological changes

The water balance and the discharge possibilities of the IJsselmeer will change in response to climate change. Sea level rise will reduce the discharge capacity of the sluices in the Afsluitdijk. During winter, when large amounts of water must be discharged, this causes a rise of the lake level. Because of the higher summer target level, the discharge capacity of the Afsluitdijk sluices in summer will be higher than in winter. Combined with a lower input, sea level rise will not necessarily result in higher summer lake levels. In the winter season the discharge into the lakes from the River IJssel and the surrounding areas will increase, while in the summer season a decrease is foreseen, due to reduced IJssel flow and a larger intake of water for the surrounding polders. Consequently, increasing amounts of water have to be discharged from the IJsselmeer into the Wadden Sea in the winter season. Even without sea level rise this would give already cause higher lake levels in winter. Lake levels may become lower during dry summers when the influx through the IJssel becomes less than the water demand from the lakes.

The combined effect of a changing water balance with a sea level rise was analysed for the climate change scenarios. Figure 12.4 gives the change in mean and maximum lake levels in the IJsselmeer for the three climate change scenarios. About 90 % of the change in lake level in winter is caused by sea level change (Van der Slikke, 1996). The increase can further be attributed to the increase of the inflow through River IJssel. Generally, the increase in mean IJsselmeer lake level during winter is about half of the sea level rise, while the increase of maximum level is about the same as sea level rise.

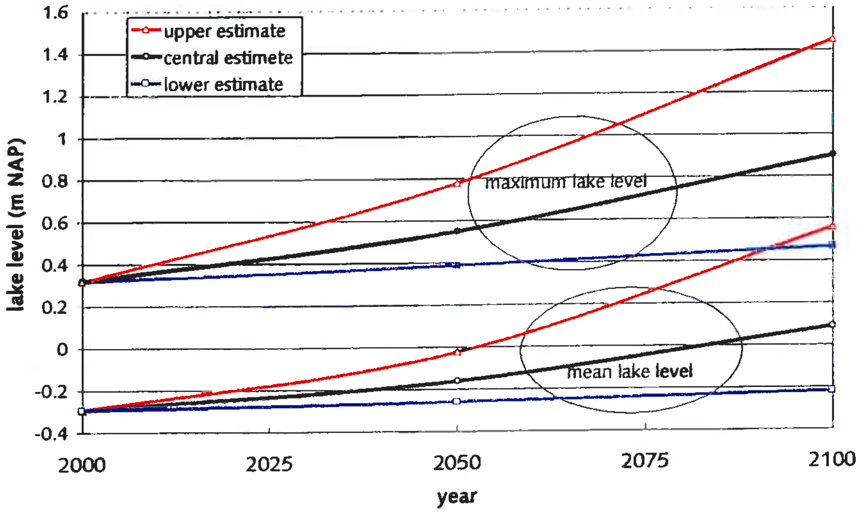

Figure 12.4 Effect of climate change on mean and maximum lake level during winter half year of the IJsselmeer

Winter lake levels
Higher lake levels in the IJsselmeer will cause higher levels in the other lakes as well. Figure 12.5 shows the mean winter lake levels for IJsselmeer and Markermeer for the upper and central estimates. Mean lake levels in the Randmeren are slightly higher than those in the Markermeer, because of the higher target level. Nevertheless, the mean lake levels of both lakes are almost the same in the climate scenarios for the year 2100. The levels of Markermeer and Randmeren do not increase as much as in the IJsselmeer. Lake levels in the Randmeren are not affected when the sea level change is still moderate (central estimate 2050), because of their higher target level. Mean lake levels in winter, however, will become higher than the summer target level. In the central estimate scenario this takes place between 2025 and 2050. The variability in lake levels will thus become larger in response to climate change.

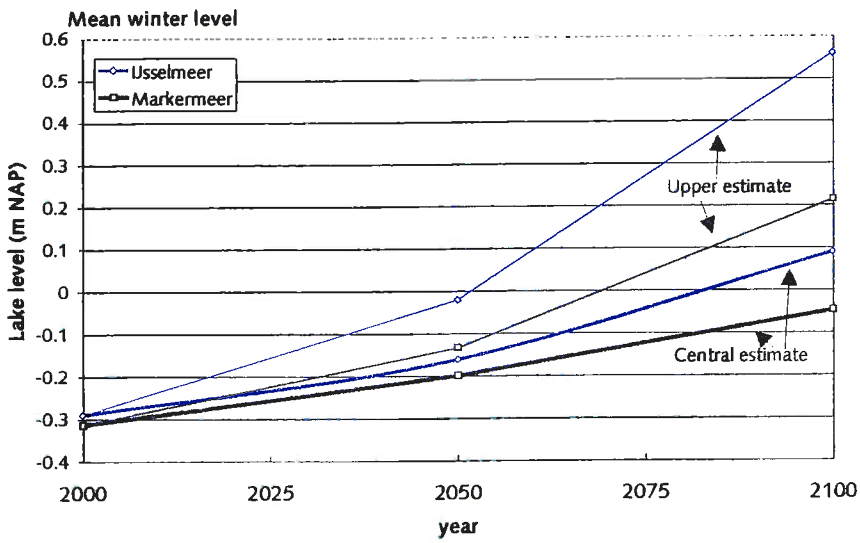

Figure 12.5 Effect of climate change (upper and central estimate) on the mean winter lake level of IJsselmeer and Markermeer

Summer lake levels

The influence of the increased sea level on the IJsselmeer summer levels is not noticed immediately, due to the higher summer target levels. As long as sea level rise is less than about 0,5 m the summer target levels can be maintained for most of the time; the increase in mean lake level is then only 5 cm. The lower discharge into the lakes will reduce the summer levels, as can be seen in figure 12.6 for the central estimate for 2050. Nevertheless, in the upper estimate scenario for 2050 the mean lake level already increases due to sea level rise. It must be noticed here that the higher lake levels in winter control the mean lake level in the summer season. According to the scenarios used in the summer season there will be less water available, mainly due to a lower discharge of the river Rhine and a higher evapotranspiration. Consequently, the summer lake levels may decrease below target level. Figure 12.7 illustrates the case of a dry summer where the input into the lake is smaller than water uptake from the lake into the polders. The lake level drops below target level for REF1995. This reduction in lake level increases in the case of the climate scenarios. However in the Upper scenario for 2100 the lake level does not drop below target level, because of the major sea level rise.

The increase in mean winter lake level is larger than the increase in mean summer lake level. Eventually, the mean lake levels in the winter season will become higher than the mean summer lake levels. This situation is assumed favourable for nature (Iedema et al., 1996). Even when the mean winter lake level is still lower than the mean summer lake level, maximum winter levels will be higher than in summer.

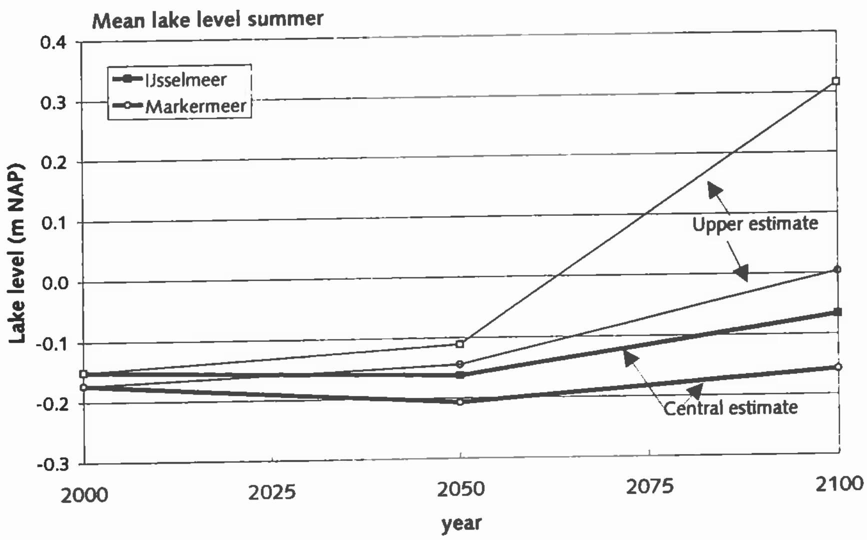

Figure 12.6 Effect of climate change (upper and central estimate) on the mean summer lake level of IJsselmeer and Markermeer

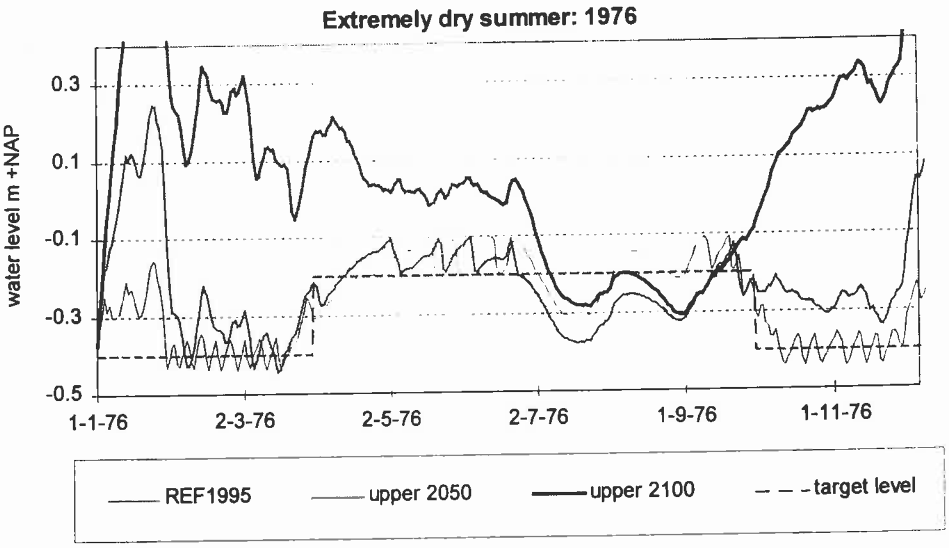

Figure 12.7 Lake levels IJsselmeer during 1976 for the upper estimate scenario. Calculated with BekkenWin

Amsterdam-Rijnkanaal/Noordzeekanaal

The Amsterdam/Rijnkanaal and Noordzeekanaal are dependent on sea level for the discharge of excess water. The target levels can still be maintained reasonable at the cost of additional pumping (figure 12.8). Maximum levels will increase however above levels which can cause problems. Dependent on the water management strategy the inlet of the water from Markermeer to Noordzeekanaal will be influenced. When the present management is applied the inlet of Markermeer water into the Noordzeekanaal will decrease and that will increase the salt intrusion into the Noordzeekanaal.

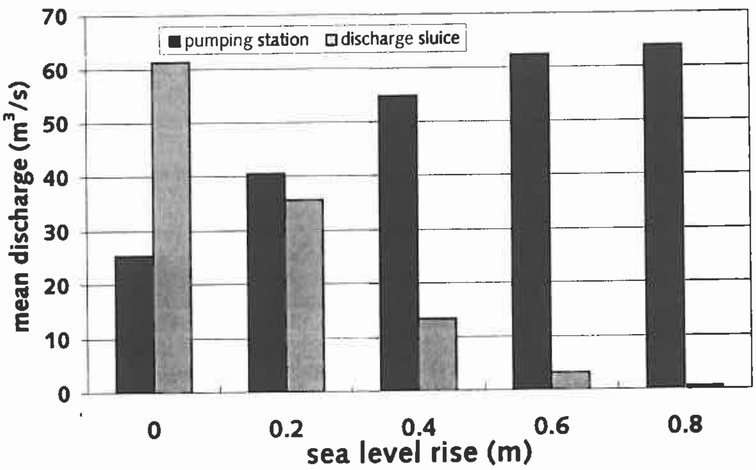

Figure 12.8 The effect of sea level rise on the discharge the Noordzeekanaal to the North Sea by the discharge sluice and the pumping station at IJmuiden. The discharge is a average value over a the period 1983 until 1995.

12.3.2 Implications for the user functions

Safety against flooding
Climate change will lead to a rise of mean winter lake levels of the IJsselmeer and Markermeer (Lorenz et al., 1998). This will effect the design levels for dike crests around the IJsselmeer and Markermeer. All climate change scenarios show an increase of design levels for the dikes. Along the western border of the IJsselmeer the rise is between 0.4 to 0.5 m according to the central estimate for 2050. This is equal to about twice the sea level rise (figure 12.9). The increase along the eastern border of the IJsselmeer is about 0.2 m (according to the central estimate for 2050), approximately equal to the rise of sea level. In the upper 2100 scenario, lake levels control the design levels at all locations around the IJsselmeer.

Water management for surrounding polder areas
Higher lake levels during the winter half-year will limit the drainage capacity of excess water from the surrounding polders into the IJsselmeer. Higher lake levels in the winter season give rise to a higher head loss for the pumping stations that discharge into the IJsselmeer Area. In addition, because of higher winter rainfall, larger quantities of water must be discharged from the polders. Therefore, is expected that additional pumping capacity (up to 35% for some stations). In the investigated cases, the additional pumping capacity needed was larger than the increase in precipitation.

During the summer, the demand of water for the polders will rise, due to the increased temperature and resulting evapotranspiration envisaged by the climate change scenarios. At the same time, summer discharge of the River IJssel into the IJsselmeer will reduce. This may lead to summer water levels below the target level. Because of the head loss, water supply to the polders becomes limited when the lake levels drops below NAP -0.20 m. The additional capacity needed in the case of the upper estimate for the year 2100 along with the present water management would be about 10 m^3/s.

Ecology
The ecological effects depend on lake levels, residence times and chloride concentrations. Sea level rise will result in a more natural lake level regime with winter levels higher than summer levels. It is however not clear whether the difference between winter and summer level is optimal for ecology. The effect of climate change on the average residence time of the water in the lakes is small. In the central estimate for 2050 the maximum residence time in summer of the IJsselmeer will increase by 14%. The REF2050 scenarios, which are meant to be beneficial for ecology because of the inverted target levels, also reduce the residence times in extremely dry summers. This is advantageous for water quality in summer: lower residence times can decrease the seasonal algae growth. Climate change is not expected to have an important effect on the chloride concentration of the IJsselmeer, Markermeer and Randmeren, assuming that the incoming salt concentration in the river Rhine at Lobith remains unchanged.

Navigation and recreation
Climate change will lead to a rise in water levels in the IJsselmeer area most of the year. During dry summer periods, lake levels may temporarily drop below target, but are not expected to go below the present winter target of NOP - 0.4 m. Therefore, inland navigation in this area will not be affected by climate change.

The effects for recreation are considered to be of minor importance. Higher temperatures are positive for water recreation, but also might increase the risk of algae bloom and botulism. Changes in summer water levels are not expected to be so large that beach recreation will be affected.

12.3.3 Implications under alternative water management

The effects given so far have been analysed assuming the present day water management policy and rules. Both technical measures and management policy might be applied to cope with changing conditions as well as demands of the functions. This is presently being investigated in the WIN-project (Iedema & Breukers, 1998). One of the alternative strategies for water management that may be adopted in future is a strategy with more 'natural' target levels, and shallow forelands along the lakes' borders. Such a situation has been implemented in the REF2050 scenario that was derived from the WIN-project. This scenario considers high target lake levels in winter (NAP +0 m) and low levels in summer (NAP -0.40 m). Considering the results obtained for the present-day target levels it can be concluded that these alternative target levels well anticipate the effects of climate change. However, additional measures must be applied to fulfil all demands of the functions of the lakes.

Higher levels in the winter season give a higher discharge capacity, which anticipates sea level rise. To mitigate an increase of flooding risk this REF2050 scenario considers the construction of shallow forelands at a level of NAP +0.20 m and 30 m wide along all lake borders. These forelands strongly reduce wave height, since the shallow zones cause the waves break before reaching the dike. To show the effect of the higher target levels, a model run is carried out with only the higher target levels and no forelands. The application of the REF2050 scenario would imply a reduction of the dike crest design levels around the IJsselmeer and 1 to 2.5 m (figure 12.9). In the Makermeer, however, there are already many forelands present, which means that this measure cannot compensate for a rise of extreme water levels. Here, the effect of the lake level rise is about the same as the dike crest design level rise without forelands.

Ytsma (1999) studied the mitigating effect of shallow forelands, compared to the rising of the dikes. Shallow forelands could always compensate the loss in safety due to climate change. In the case of the Upper estimate for 2100, with REF2050 target levels ('WSV-scenario'), the mitigating effect of forelands is still adequate to compensate the effect of increased lake levels (figure 12.9). Lake levels are hardly different from the upper estimate for 2100 with REF1995 target levels. Ytsma (1999) found that in case of a moderate climate change it is more cost-efficient to rise dikes than to create shallow forelands. However, under conditions of the upper estimate for 2100 creating shallow forelands would be cheaper at 60% of the examined dike sections. In the comparison of the costs the additional ecological value of forelands was not incorporated.

Lower lake levels in summer are unfavourable for the water supply to the region, and would demand additional pumping capacity for water intake from the IJsselmeer. The lower summer lake target levels will however rise due to sea level rise.

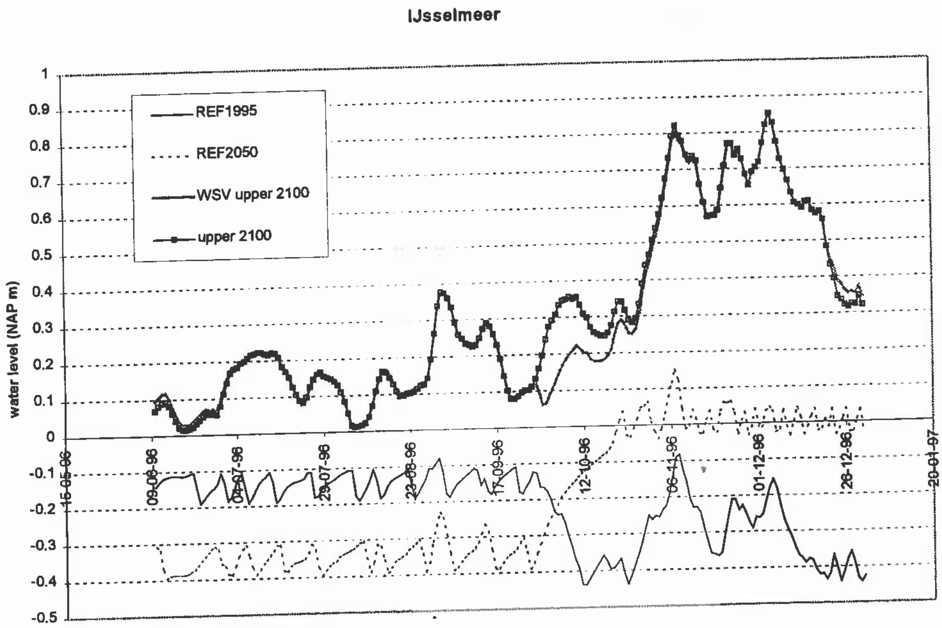

Figure 12.9 Lake levels in the IJsselmeer for the REF2050 and REF1995 scenarios, without climate change and for the upper estimate for climate change for the year 2100. Without climate change the two management policies give an opposite summer winter lake level. Under conditions of the upper estimate for 2100 there is almost no difference in the water levels resulting from the two management policies.

12.4 Conclusions

Climate change will have a significant effect on the IJsselmeer Area. The hydrology of the lakes is influenced by the expected change in sea level rise, river discharge and precipitation. This will generally result in higher lake levels, with exception of dry summers when a decrease in lake levels may occur. All functions that are dependent on the lake levels are therefore affected by climate change.

Due to the expected sea level rise, the winter lake levels rise such that the target level can no longer be maintained. The increase in discharge of the IJssel and additional discharge into the lakes will add to this increase. The rise of the mean winter lake level in the IJsselmeer is about half of the sea level rise, while the increase of extreme lake levels is the same as the rise of sea level.

Summer lake levels are only little affected by sea level rise. If sea level rise is less than 0,5 m the mean summer level exceeds the target level only by about 5 cm. Due to a reduced water inflow from the IJssel and an increased demand from the polders, periods of water shortage in summer will increasingly occur. As a result, summer lake levels may drop below the target level. The target levels in the Amsterdam/Rijnkanaal and Noordzeekanaal can still be maintained, but at the cost of additional pumping. Maximum levels, however, will increase. Under the present water management, the water flow from the Markermeer into the Noordzeekanaal will decrease, which will increase the salt intrusion into the Noordzeekanaal.

12.4.1 Implications for the user functions

Safety
The increase in the winter lake levels will result in a decrease in safety against flooding in IJsselmeer and Markermeer. The design levels of the dike crest increases from about the increase in sea level up to 2 times the sea level increase. Dike sections along the eastern side are more affected by the additional rise due to wind set-up than along the western side of the lakes. Furthermore, all results depend on the important assumption of a constant wind regime.

Water management of surrounding areas
Higher lake levels during the winter half-year will cause problems for the discharge of water from the surrounding polders into the IJsselmeer Area. It is expected that additional pumping capacity (up to 35% for some stations) is needed due to the additional head loss and also because of the greater quantities to be discharged during winter. In summer, limitations in the water supply to the surrounding areas will arise when the lake levels drop beneath the summer target value of NAP -0.20 m. The water deficit in summer will increase with increasing temperature.

Ecology
Higher winter levels and low summer levels are beneficial for ecology. Both climate change and the REF2050 water management scenario are expected to lead to such conditions. The effect of climate change on the average residence time of the water in the lakes is small. The reduction in residence time is advantageous for water quality in summer. Climate change is not expected to influence chloride concentrations in the lakes, assuming an unchanged quality of incoming Rhine water.

12.4.2 Water management alternatives and measures

When no water management measures are adopted, climate change may lead to a situation where the actual lake levels are very different from the target level during almost the entire year. Both technical measures and management policy might be applied to cope with changing conditions as well as demands of the functions. Technical measures may include additional discharge capacity of the discharge sluices in the Afsluitdijk. However, this may be ineffective when sea level rises. Building additional pumping stations leads to high cost in the first place. In addition, it goes towards a water management style that is more depending on technical measures instead of natural processes, which is undesired.

Alternative water management strategies, such as considered in the REF2050, might be adopted, which allow a more natural cycle of water levels, with higher winter target levels than summer target levels. Such a strategy would anticipate the effects of sea level rise and water availability. To maintain the current safety levels, shallow forelands can be created along the lake's banks. This reduces wave height and leads to more natural banks of the lake. This measure is only effective where there is no foreland in the present situation. In the REF2050 scenario the summer target level is lowered to NAP -0.40 m. This will demand additional capacity for water inlet into the surrounding polders. These lower summer lake target levels will be exceeded when the sea level rises. Still, periods of water shortage during dry summers are expected to occur more frequently.

13 Impact of climate change and land subsidence on the water systems in the Netherlands

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Hank A.P.H. Vermulst
Hans Middelkoop

13.1 Introduction

This chapter addresses the impacts of climate change and land subsidence on the hydrology of the terrestrial areas in the Netherlands, in terms of water quantity and water quality. In addition, the impacts of these hydrological changes on water system functions have been considered. The impacts have been computed on a nation-wide scale with a comprehensive set of linked models, including hydrological, eco-hydrological and agro-hydrological models. Literature research and interviews with experts from different water system sectors resulted in additional aspects of the possible impacts of climate change. A more detailed described is given by Haasnoot et al., (1999).

13.2 Modelling approach

To asses the impacts of climate change different climate scenarios have been compared to two reference scenarios, which reflect the current situation (REF1995) and the hydrological situation for the year 2050 (REF2050). The latter includes autonomous developments, which are to occur without influence of climate change. The autonomous developments foreseen in this study include land subsidence (figure 4.1, Haasnoot et al. 1999), change in land use (Kors et al., 1997) and the autonomous sea level rise. The climate scenarios considered are a central estimate for the year 2050 (+1°C) and an upper estimate for the year 2100 (+4°C). The scenarios are covered in detail in chapter 4.

The hydrological situation of the reference and climate scenarios has been computed nation-wide with the models NAGROM and MOZART, connected with the model interface MONA (Vermulst et al., 1999; De Haan, 1998). NAGROM (De Lange, 1996) is a steady state model for the saturated zone, based on the Analytic Element Method (AEM; Strack, 1989). The hydrological top system, which is defined as the layer above the upper semi-permeable layer, is modelled as an area with one or two drainage systems. The upper boundary condition of the hydrological top system is given by the groundwater recharge. The behaviour of the hydrological top system is modelled in a lumped manner, using a linear relation between groundwater heads in the first aquifer and the flux towards the different drainage systems (De Lange, 1996).

MOZART (Ontwikkelingteam NAGROM-MOZART-DEMNAT-AGRICOM, 1997) computes vertical transport through the unsaturated zone. A grid of 500-m x 500-m resolution covers the hydrological top system. Each grid cell (plot) is modelled as a vertical soil column, consisting of an effective rootzone and subsoil. Interactions between adjacent plots are assumed to take place through the first regional aquifer, by means of an upward or downward seepage flux. This seepage flux expresses the lower boundary condition for a plot. The upper boundary condition is given by ten-day-interval time series of precipitation and evapotranspiration rates. MOZART considers three different drainage systems, representing canals or brooks, ditches and artificial drains. The drainage to the different drainage systems is computed with so-called drainage functions, which are broken linear relations between groundwater level and drainage flux.

Within the REF2050 and the climate scenarios, drainage levels have been adapted to the estimated land subsidence rates. For the climate scenarios, the groundwater recharges have been changed as a result of the changes in precipitation and evapotranspiration (transpiration and evaporation), according to table 13.1. In addition, the surface water levels of the North Sea, IJsselmeer, the estuaries and the rivers Rhine and Meuse, which are head boundary conditions within NAGROM, were adapted according to table 13.2.

The calculated hydrological changes have been used as input for the ecohydrological model, DEMNAT (Witte, 1990), and the agrohydrological model, AGRICOM (RIZA, 1995). AGRICOM estimates the costs and benefits for agriculture, using information on e.g. the amount of sprinkling needed and groundwater levels. Damages are calculated from IKC-tables (IKC, 1993), which contain the relation between the drought and water logging damage for different combinations of mean highest groundwater level (MGHL) and mean lowest groundwater level (MLGL) for different crops and soil types.

The Dose Effect Model for terrestrial NATure (DEMNAT) considers the impact of hydrological changes on plant species richness of several terrestrial ecosystems with dose-effect functions. These functions reflect an empirical relation between the hydrological changes and the changes in botanical quality of eighteen ecosystem types (ecotopes). The ecotopes (Van der Meijden et al., 1996) are classified on vegetation structure and abiotic site factors. To weigh the ecological effects with respect to the importance for nature conservation in the Netherlands the results are also expressed as the change of conservation value. DEMNAT considers rare ecotopes to have a higher conservation value than more common ecosystems. Furthermore, an expansion of an ecosystem is always judged as positive.

Table 13.1 Characteristics of the two climate scenarios

Scenario	Temp. Rise	Sea level rise	Δ winter precipitation	Δ summer precipitation	Δ reference evaporation	Δ transpiration
CEN2050	+ 1 °C	+ 25 cm	6%	1%	4%	- 4 - - 12 %
UPP2100	+ 4 °C	+ 110 cm	25%	4%	15%	- 8 - - 25 %

Table 13.2 Change in sea level

Scenario	Noordzee	Ijsselmeer	Markermeer	Randmeren	Noordzeekanaal	Rivers
REF2050	10	2	2	1	0	0
CEN2050	25	6	4	2	1	-8
UPP2100	110	63	30	26	3	-30

13.3 Impact on hydrology

Autonomous developments

The results of the hydrological modelling are given in box 13.1, in terms of changes in mean spring groundwater levels (MSGL), changes in annual discharges from different catchment areas, changes in salt load of surface water originating from groundwater, and the amount of externally supplied water.

The autonomous developments, simulated within scenario REF2050, have a relatively small effect on the average groundwater level. Changes occur especially in areas where land subsidence is considerable. In these areas (such as the brook valleys in the province of Friesland, and the peat areas in the province Zuid-Holland), the increased gradient in surface elevation accelerates infiltration and upward seepage. This results in a lowering of the groundwater level in infiltration areas and higher groundwater levels in seepage areas. Local effects of land subsidence are expected to be greater as it is assumed that water management will keep up with land subsidence by adjusting the drainage levels.

Changes in land use may result in a change of groundwater recharge and therefore changes in groundwater levels and discharges. REF2050 does not affect the average discharges, but areas with considerable land subsidence show a slight increase in average discharges and adjacent areas without land subsidence obtain a higher regional position and exhibit a slight decrease of the average discharges.

In determining the change in salt loads, it was assumed that the salt concentrations in the shallow groundwater would remain the same: salt transport is several orders of magnitude slower than water transport. Changes in salt loads amount up to approximately 500 kg/ha/year. Dependent on the ratio between net precipitation and upward seepage, these changes correspond with changes of chloride concentrations of 50 - 200 mg/l. Box 13.1 learns that changes in salt loads are determined by land subsidence and the authonomous sea level rise, rather than by climatic changes. The upper estimate for 2100 shows approximately twice the effects of the REF2050 and CEN2050 scenarios, but this is caused by the fact that we assumed doubled land subsidence figures.

Climate change

Global warming results in an increase of the precipitation surplus and therefore in more infiltration in infiltration areas and more upward seepage in brook valleys. This effect is most apparent in the Southern and Eastern parts of the Netherlands (figures 13.1 and 13.2). As the precipitation surplus increases, the average of the mean spring groundwater levels will also rise. The model results show an average increase of 4 - 5 cm for a temperature rise of 1 °C (CEN2050) and 10 - 15 cm for a temperature rise of 4 °C (UPP2100). However, the effects of global warming are rather diffuse; the rise of the groundwater levels strongly depends on the drainage intensity of an area. If drainage intensities are high, the extra net precipitation is discharged into surface waters, rather than stored in the shallow groundwater system. In the Holocene deposits, groundwater levels are determined by the surface water levels rather than by precipitation. Therefore, the impact of climate change on groundwater levels is smaller in these areas.

Furthermore climate change results in significantly more discharge in most areas. These changes of the annual discharge (12 % and 25 %) are approximately the same as the increase in winter-precipitation foreseen in the scenarios. The amount of water that is supplied from the rivers (Rhine and Meuse) in periods of drought shows only small changes in the western part of the Netherlands. However, within this survey it was assumed that the amount of water supplied equals the amount of water. When linking MOZART to the Distribution Model, seasonal variations of changed river discharges and precipitation can accounted for as well.

BOX 13.1 Results hydrological modelling

Table A Distribution of changes in mean spring groundwater level (%)

Scenario	< -5 cm	-5 - 0 cm	no change	0 - +5 cm	+5 - + 10 cm	+10 - +25 cm	> +25 cm
REF2050	18.2	11.7	44.6	7.6	4.2	6.1	7.6
CEN2050	5.3	5.8	30.7	31.21	13.5	7.4	6.1
UPP2100	5.2	.4	21.7	18.4	16.5	22.5	11

Table B Distribution of changes in salt loads (kg/ha/year) from groundwater as percentage area of total area

Scenario	< -500	-400	-100	no change	0 - + 100	-400	> + 500
REF2050	0.5	1.3	9.2	56.1	26.2	5.0	1.7
CEN2050	0.4	1.3	7.4	56.1	27.1	5.4	2.3
UPP2100	0.4	1.3	4.7	55.8	27.2	5.5	5.0

Table C Distribution of relative changes in annual discharges (%) as percentage area of the total area

Scenario	< -5	-5-0	0 - +5	5-10	10-20	20-30	> +30
REF2050	3.5	21.8	64.4	8.8	0.6	0.8	0
CEN2050	0.5	0.4	1.9	57.2	38	1.2	0.8
UPP2100	0	0	0.9	0.3	19.8	62.1	17

Table D Distribution of annual relative amount of externally supplied water (%) as percentage area of total area

Scenario	< -5 %	-5 - 0 %	no change	0 - +5 %	+ 5 - + 10 %
REF2050	0.2	9.7	75.2	14.7	0.0
CEN2050	0.4	20.8	71.6	7.2	0.0
UPP2100	0.5	19.8	70.4	9.3	0.0

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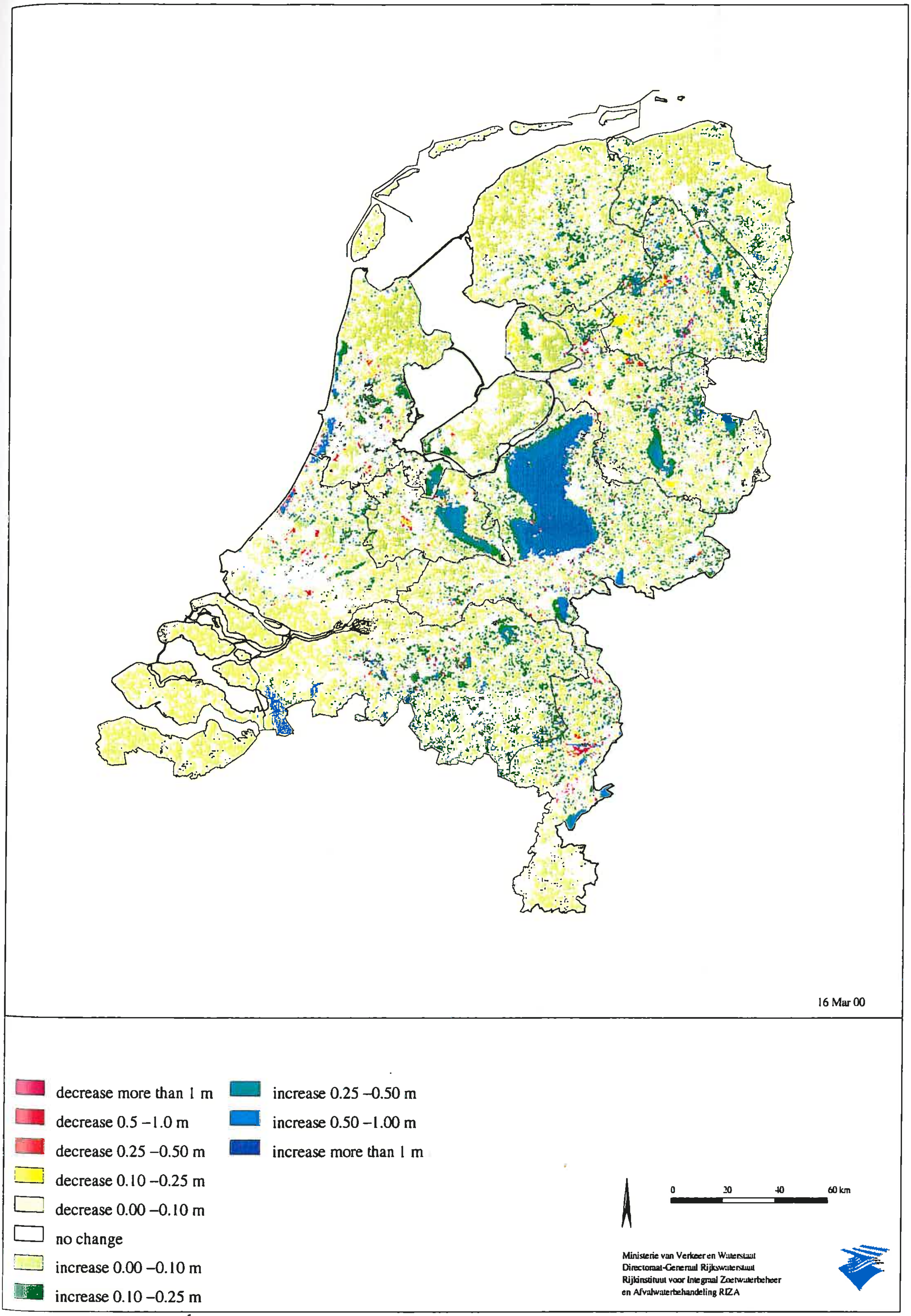
Figure 13.1 Change in mean spring groundwater level for the central estimate 2050

Figure 13.2 Change in mean spring groundwater level for the upper estimate for the year 2100


16 Mar 00
decrease more than 1 m
decrease 0.5 – 1.0 m
decrease 0.25 – 0.50 m
decrease 0.10 – 0.25 m
decrease 0.00 – 0.10 m
no change
increase 0.00 – 0.10 m
increase 0.10 – 0.25 m
increase 0.25 – 0.50 m
increase 0.50 – 1.00 m
increase more than 1 m
0
20
40
60 km
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meer dan 1 m te diep
0.5 – 1.0 m te diep
0.25 – 0.50 m te diep
0.10 – 0.25 m te diep
0.00 – 0.10 m te diep
binnen Gt-bereik
0.00 – 0.10 m te hoog
0.10 – 0.25 m te hoog
0.25 – 0.50 m te hoog
0.50 – 1.00 m te hoog
meer dan 1 m te hoog

0 20 40 60 km

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13.4 Impact on ecological functions

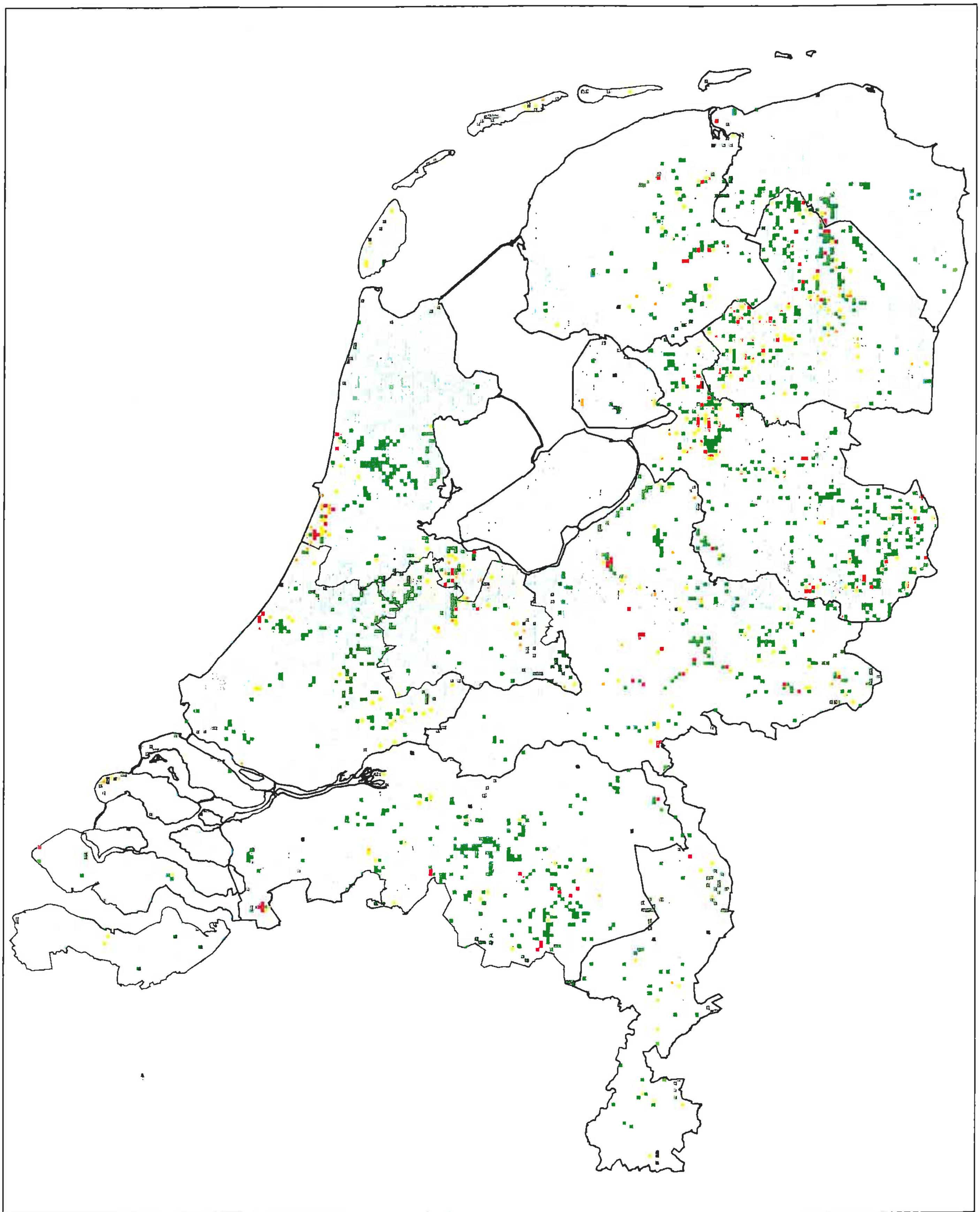
Table 13.3 presents the net ecological effects in terms of nature conservation values calculated with DEMNAT. The results indicate that autonomous developments have limited ecological effects on a nation-wide scale when compared to the applied climate changes. A strong climate change (scenario UPP2100) would result in a major increase of the conservation value, such that approximately 42 à 52 percent of the maximum possible ecological restoration would be reached. However, the spatial distribution (figures 13.3 and 13.4) shows both areas with losses and gains of nature conservation values. The changes can be attributed to either changes in mean spring groundwater level or changes in upward seepage.

DEMNAT indicated that autonomous developments may lead to an increase of the nature conservation values in the peat areas of the Holocene part of the Netherlands. In areas adjacent to areas with land subsidence and the brook valleys, the upward seepage and groundwater level decreases, which reduces the nature conservation value. Climate change largely eliminates these effects and, moreover, leads to an increase of the conservation possibilities of wet ecotopes, such as herbaceous and wood vegetation on sites with little or no nutrients.

Next pages

Figure 13.3 Change in nature conservation value for the central estimate for the year 2050.

Figure 13.4 Change in nature conservation value for the upper estimate for the year 2100.



- less than -2
- -2 - -1
- -1 - -0.5
- -0.5 - -0.001
- -0.001 - 0.001
- 0.001 - 0.5
- 0.5 - 1
- 1 - 2
- more than 2

0 30 60 Kilometers

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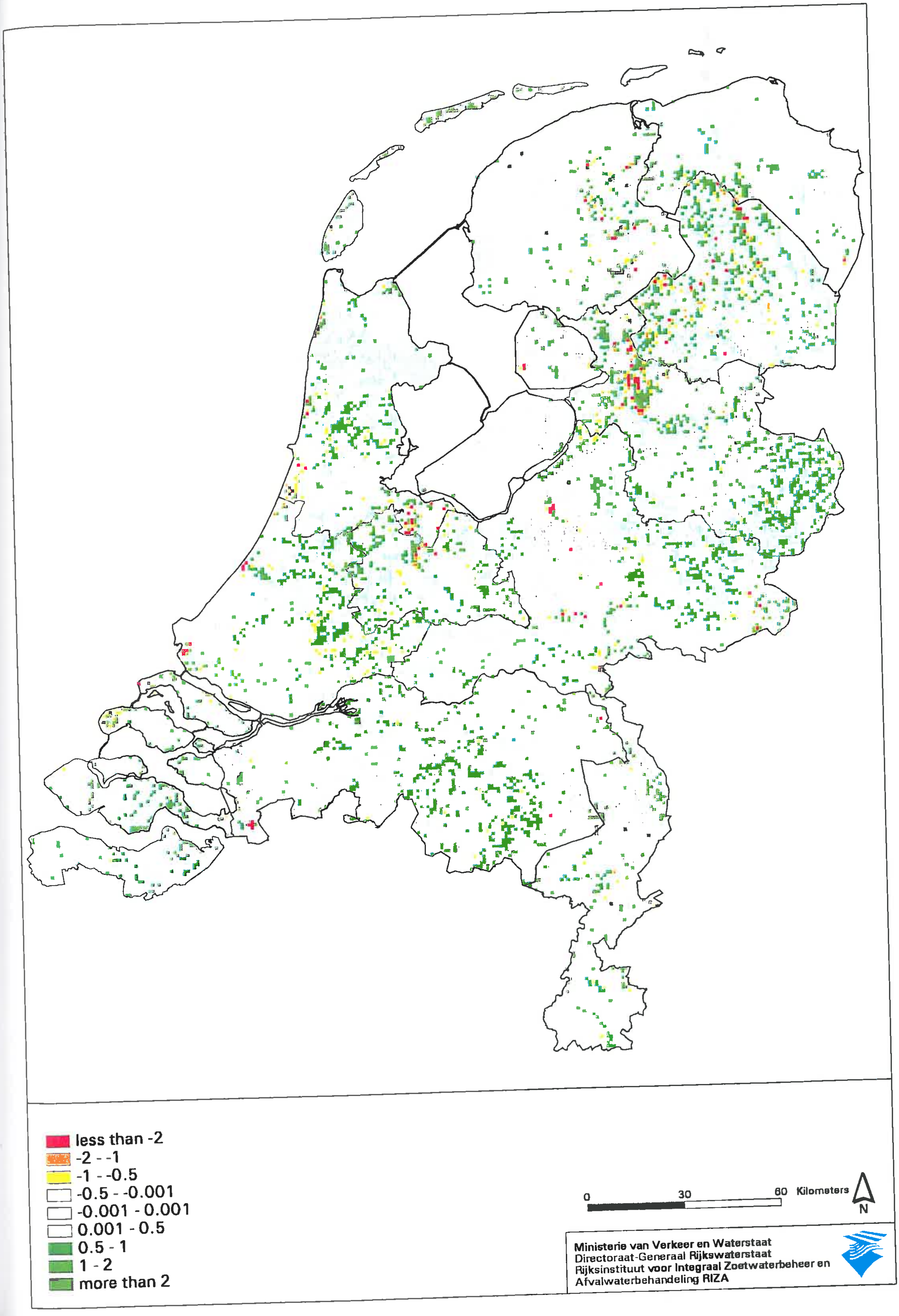

less than -2
-2 - -1
-1 - -0.5
-0.5 - -0.001
-0.001 - 0.001
0.001 - 0.5
0.5 - 1
1 - 2
more than 2
0
30
60
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Table 13.3 Changes in nature conservation values in conservation value units (cvu)

Scenario	dN (cvu)	dN/N_{pres} (%)	$dN/N_{restoration}$ (%)
REF2050	454	1	5 à 6
CEN2050	1599	4	18 à 22
UPP2100	3787	10	42 à 52

dN — change conservation value (Nscenario-Npres)
Npres — present conservation value
Nrestoration — difference between the present conservation value and the maximum possible nature conservation value, based on the TRENDBREUK scenario (Kors *et al.* 1997)

One of the major environmental problems in the Netherlands is desiccation, which is mainly caused by extensive drainage of agricultural land and the extraction of groundwater. Although wetter climate conditions may alleviate the desiccation problems in most nature conservation areas, the problems will not be solved. In most cases, this effect will be too small to solve the desiccation problems, because the mean drop of groundwater levels of the last decades is approximately 30 cm. A rise of groundwater levels of 30 cm or more is only reached in a small part of the desiccated nature reserves.

The relations between vegetation and its abiotic surroundings (hydrology, soil, atmosphere), are extremely complex. Focusing on the hydrological changes only is not sufficient for a reliable prediction of the impact of climate change on nature. Important influences that have not been taken into account are for instance the effect of temperature rise and an increase of atmospheric CO_2 on mineralisation and species diversity. Higher temperatures accelerate the mineralisation of soil organic matter, which may ultimately increase the nutrient content of the soil. This may influence the succession and composition of the several ecosystems (Van de Geijn et al., 1998), but may be mainly favourable for plant species adopted to high nutrient conditions and that are less appreciated because of their common occurrence. Arp et al. (1998) concluded that these negative effects of increased nitrogen concentration would be stimulated by increased atmospheric CO_2 concentration, as this causes an increase of biomass. Plant species with a C_3 photosynthesis will benefit more from the CO_2 rise than C_4 species, which will also change the composition of vegetation.

13.5 Implications for agriculture

Hydrological changes will influence the costs and benefits for agriculture. The results of the model AGRICOM are given in table 13.4 in terms of total costs in millions DFL summed for the whole Netherlands. Figures At the scale of the individual farmer, the changes might be more extreme than these averages. The total drought and water logging damage for the Netherlands will decrease because in this scenario a total of 2360 km^2 agriculture areas are replaced by nature or urban area. It was assumed that the water management would keep up with the land subsidence by adjusting the drainage depth. When the surface water levels will not be lowered artificially in response to land subsidence, the water logging damage will increase considerably and drought damage will show a (smaller) decrease (Kors et al.,1998).

Under the applied climate scenarios of climate change, both drought damage decreases and water logging damage increase, when summed for the whole

Netherlands. The central estimate for 2050 results in a decrease of 28 and 66 Millions DFL for the drought and water logging damage respectively. Comparison with the reference scenario for 2050 indicates that the higher groundwater levels induced by climate change might reduce drought damage by about 6 Millions DFL ht damage and rise the water logging damage by about 52 Millions DFL. In case of the upper estimate for the year 2100, the drought damage decreases by 4 fl/ha, which is similar as according to the central estimate for 2050. However, the changes at regional scale are larger than in case of the central estimate 2050. In case of the upper estimate 2100 the total water logging damage with approximately 162 Millions DFL higher than under conditions of the REF2050. Because of the relative high invariable costs, climate change hardly rises the total sprinkling costs in the Netherlands.

Table 13.4 Changes in drought damage, water logging damage and sprinkling costs summed for the whole Netherlands (Millions DFL)

Scenario	Change drought damage (M DFL)	Change in water logging damage (M DFL)	Change sprinkling costs (M DFL)	Total damage (M DFL)
REF2050	- 22	- 118	- 0,8	- 140.8
CEN2050	- 28	- 66	- 1,4	- 87.4
CEN2050 * (no land use changes)	- 6	+ 57		
UPP2100	- 30	+ 44	- 1,2	+ 12.8

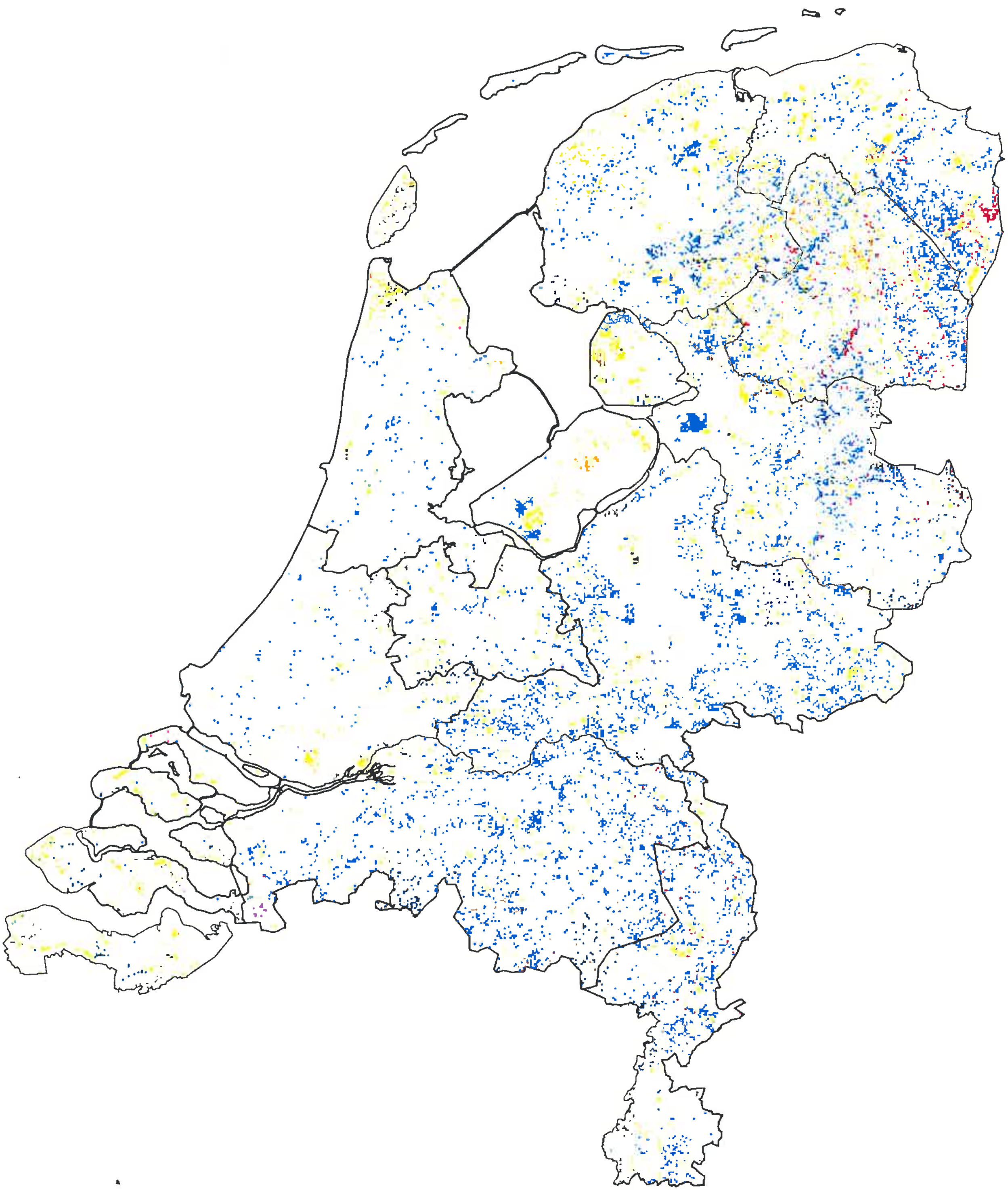
Next pages:

Figure 13.5 Change in drought damage for agriculture for the central estimate for the year 2050.

Figure 13.6 Change in drought damage for agriculture for the upper estimate for the year 2100.

Figure 13.7 Change in water logging damage for agriculture for the central estimate for the year 2050.

Figure 13.8 Change in water logging damage for the upper estimate for the year 2100.



Change drought damage CEN2050

- increase more than 200 fl/ha
- increase 50 - 200 fl/ha
- increase 5 - 50 fl/ha
- change 0 - 5 fl/ha or replaced
- decrease 5 - 50 fl/ha
- decreae 50 - 200 fl/ha
- decrese more than 200 fl/ha

0 20 40 60 Kilometers

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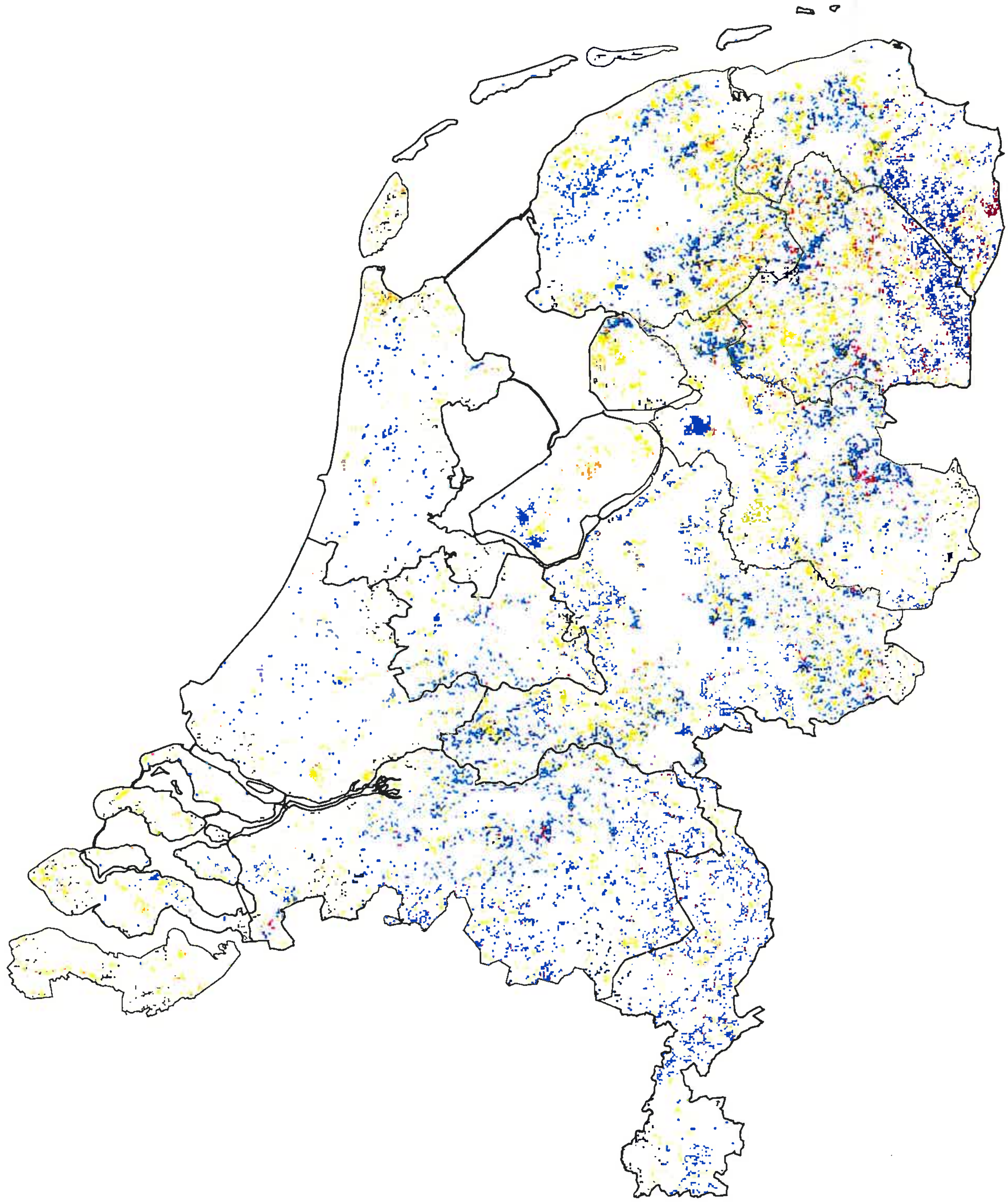

Change drought damage UPP2100

- increase more than 200 fl/ha
- increase 50 - 200 fl/ha
- increase 5 - 50 fl/ha
- change 0 - 5 fl/ha or replaced
- decrease 5 - 50 fl/ha
- decreae 50 - 200 fl/ha
- decrese more than 200 fl/ha

0 20 40 60 Kilometers

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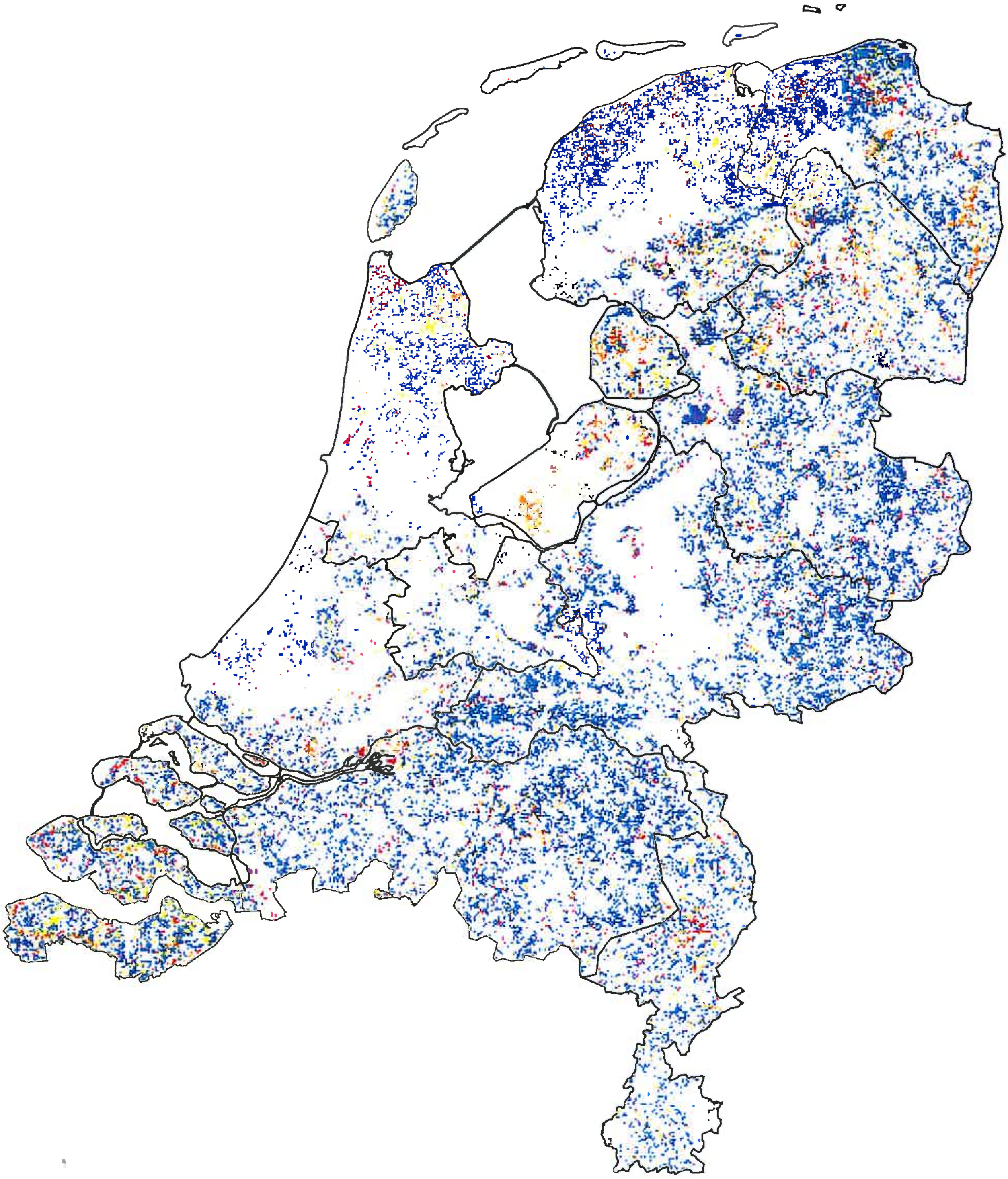

Change water logging damage CEN2050

- increase more than 200 fl/ha
- increase 50 - 200 fl/ha
- increase 5 - 50 fl/ha
- change 0 - 5 fl/ha
- decrease 5 - 50 fl/ha
- decreae 50 - 200 fl/ha
- decrese more than 200 fl/ha

0 20 40 60 Kilometers

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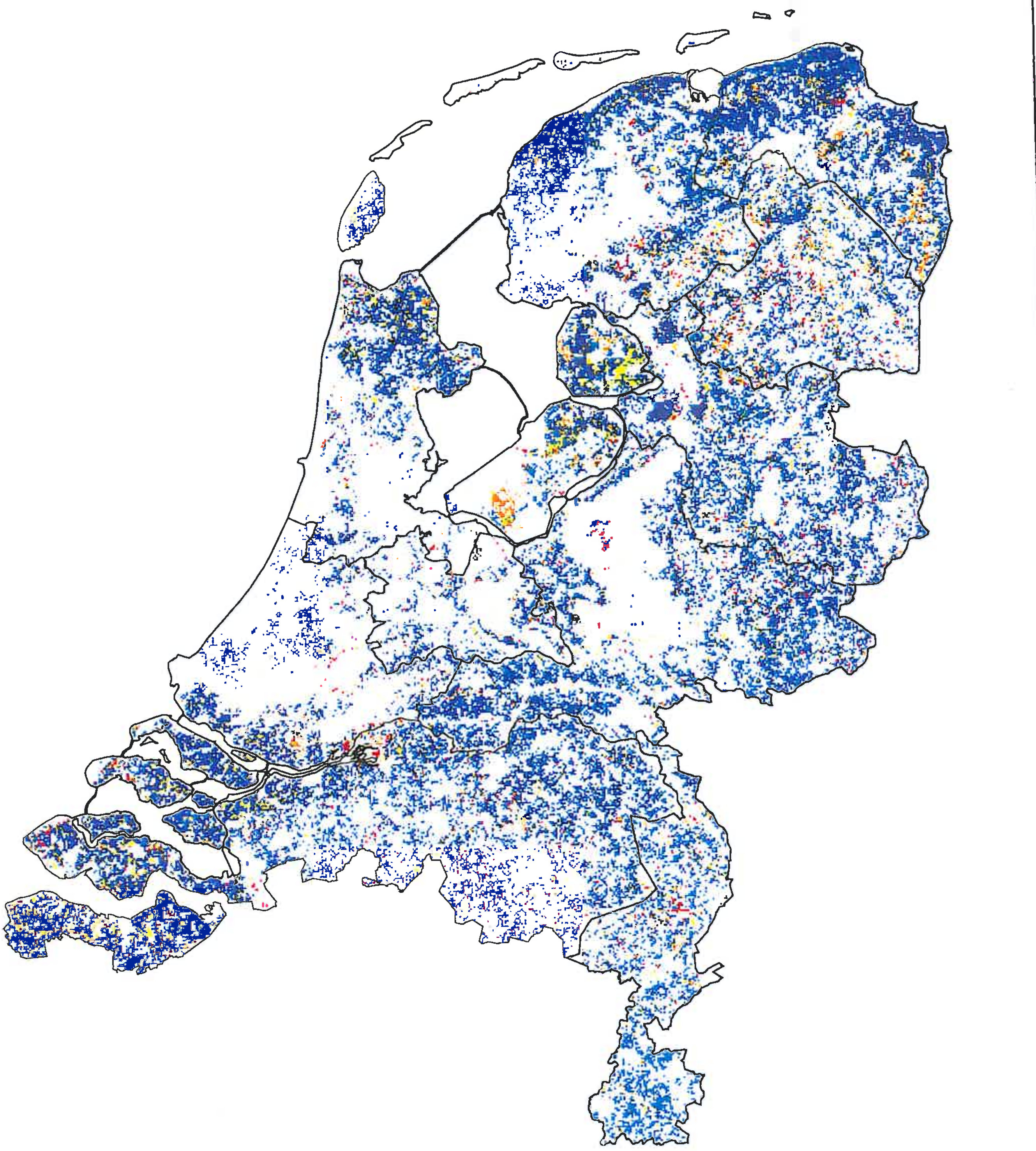

Change water logging damage UPP2100

- increase more than 200 fl/ha
- increase 50 - 200 fl/ha
- increase 5 - 50 fl/ha
- change 0 - 5 fl/ha
- decrease 5 - 50 fl/ha
- decreae 50 - 200 fl/ha
- decrese more than 200 fl/ha

0 20 40 60 Kilometers

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13.6 Conclusions and possibilities for mitigation measures

Modelling hydrologcial changes and impacts

Implementing a nation-wide groundwater model, estimating its model parameters, and running it for a variety of scenarios with changed elevation, land use and climate has demanded a major effort. In the present model versions, it had to be assumed that the supply of water in summer is not limited. However, under the assumed climate scenarios, the availability of water from the Rhine during summer is expected to reduce. As a result, summer groundwater levels may have been over-estimated by the current model.

On the average, the effect of climate induced changes in transpiration on the groundwater level seems small. However, these results depend on the assumed changes in evapotranspiration. It is argued that transpiration rates of plants may reduce in response to higher atmospheric CO_2 contents, because of a more efficient transpiration. On the other hand, the growing season may become longer, plants may adapt to the new conditions, or other plant varieties may be introduced. The present uncertainties in the total effects lead to uncertainties in the modelling result, particularly for groundwater levels.

The present results provide estimates of cost and benefits averaged over larger regions, and expressed in annual totals. A more detailed picture can be obtained by considering smaller, representative areas, and evaluating potential damages for each decade instead of using mean highest and mean lowest groundwater levels. This kind of modelling requires the development of the water logging damage module in MOZART.

Autonomous changes

Soil subsidence enhances the elevation gradient between Holocene and Pleistocene areas, resulting in accelerated upward and reduced downward seepage in the Holocene area. In the reclaimed lakes in the Holocene areas, the infiltration and upward seepage decrease. At a few locations regional water discharge increases. Changes in salt loads are mainly caused by land subsidence and occur mainly in the western and northern part of the Netherlands. Land use changes (i.e. increases of nature and forest at the expense of agriculture) may lead to accelerated evapotranspiration. In the Veluwe, the province of Friesland and the coastal dunes, this may reduce groundwater levels. The results also indicate that estimates of the total damage for agriculture strongly depend on the assumed land use scenario.

Effects of climate change

Climate change will generally in a rise of the groundwater levels in springtime, while mean lowest groundwater levels (in summer) decrease. The differences between mean lowest and mean highest ground water levels increase due to the higher precipitation increase in winter and accelerated evapotranspiration in summer. The higher precipitation amounts result in a significant increase of infiltration in infiltration areas and an increase of upward seepage in areas with upward seepage. Climate change results in a significant increase in average annual discharges: approximately 12 % for CEN2050 and 25 % for UPP2100. Moreover, since precipitation extremes may increase more than average values, peak discharges from regional water systems may increase, demanding a higher storage and discharge capacity. In the province of Zeeland, sea level rise may lead to increased salinisation of groundwater. The hydrological effects of climate change as in the CEN2050 and UPP2100 scenarios are much larger than the effects resulting from soil subsidence and land use changes as considered in the REF2050 scenario. As the effects of climate change on the measured hydrological parameters appear to be non-linear; the results cannot be interpolated linearly for other scenarios.

Climate change results in a significant increase of the conservation values of wet ecosystems in almost the entire country. Furthermore, wet ecotopes may cover a larger area. Wetter conditions, as predicted by the scenarios, will decrease the desiccation problems in most areas, but only partly fulfil the water demand. Besides the hydrological changes, nature will be influenced by the CO_2 and temperature rise. Both may influence the composition of the vegetation, but these effects were not considered here.

Climate change may rise water logging damage and decrease drought damage for agriculture. The effects on a regional scale the changes may be different from the overall average due to spatial differences in hydrological conditions and climate effects on the one hand and due land use changes and the application of new crop varieties on the other hand. The total drought damage for the Netherlands increases less than proportionally with the magnitude of climate change, while water logging damage rises for more extreme scenarios, particularly in the northern and eastern parts of the country. It must be noted here, however, that in the applied modelling it was assumed that water availability from the rivers remained unchanged. Since summer flow will reduce, drought damage may turn out larger than indicated in the present study.

The assumed changes in land use have a major influence on the estimates of damage for agriculture, when calculated as a total figure for the entire country. Also, the impacts depend on the present regulations in margins in water management, and depend on the actual capacity to discharge water to prevent flooding in winter and to supply fresh water for sprinkling and flushing in summer. Particularly in the polder areas, adding pumping stations may not solve problems of water discharge in case the discharge capacity of the low-gradient storage channels is limited. Land use changes (i.e. converting agriculture land into nature) and water management measures should be guided by the hydrological changes resulting from the climate change scenarios.

14 Conclusions and policy implications

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14.1 Scenarios

The results obtained in the present study were determined by the assumed scenarios, both for climate change and autonomous developments. We have attempted to avoid a too strong dependency of the results on the climate scenario (or GCM output) used by considering the scenarios as an 'educated guess' of possible future climates. These scenarios were used as a basis for a 'what-if' sensitivity analysis rather than a prediction of future changes. To allow comparison with previous climate impact studies carried out in the Rhine basin and the Netherlands, the scenarios were chosen consistent with the scenarios adopted by Grabs et al. (1997), Werkgroep Klimaatverandering en Bodemdaling (1997), Können & Fransen (1996) and Können et al. (1997). The scenarios for the Netherlands considered here are heavily relying on the crucial assumption made by KNMI that the general circulation patterns over Europe will not change (Können et al., 1997). The scenario changes explored also cover the range of the changes (in terms of temperature rise, precipitation change and sea level rise) indicated by IPCC (1996). By using a matrix of projection years in combination with lower, central and upper estimates of the changes, a variety of scenario conditions could be explored. This approach enables comparison of possible effects for climate scenarios different from those considered here, but within the range between the lower and upper estimates.

In view of the sensitivity analyses applied here, the climate change scenarios were applied in a rather pragmatic way as absolute temperature changes and relative precipitation changes applied to a baseline climate series from various locations within the Rhine basin. This straightforward approach may pose several problems in terms of temporal and spatial resolution and the assumption of the present-day validity of the statistical distribution e.g. of precipitation under climate change conditions, which may not be realistic. The development of evapotranspiration has been largely viewed as a function of air temperature. Under different climatological conditions, evapotranspiration may change into a feedback process between increased CO_2 concentration and stomata response of plants as well as a function of future land use patterns. Future scenario analyses, therefore, should explore the potential effects of applying climate changes in a different and more sophisticated way in relation to model sensitivity and evaluate the possible hydrological implications.

Future hydrological changes and their implications also depend on developments that are independent of climate, such as land use changes, changes in water use, and landscaping measures for ecological rehabilitation. Since these autonomous developments may interfere with climate change and its effects, the REF2050 scenario was used as a second baseline in addition to the present day situation for evaluation of the climate impacts.

14.2 The Rhine basin

14.2.1 Hydrological changes

Due to climate change, the Rhine will change from a combined rainfed – snowfed river to a predominantly rainfed river. This will lead to an increase in the intra-annual variation of Rhine discharge: summer flow reduces, while winter flow increases. Total annual flow changes considerably less. This trend is found for all scenarios, the magnitude of the changes varies with the intensity of the assumed climate changes. Since the design of waterways, constructions and regulations in water management are based on the extremes in discharge, it may be expected a-priori that these are sensitive to a climate induced amplification of these extremes.

The modelling results obtained using RHINEFLOW-2 give the changes in discharge in 10-daily time steps. This time step is adequate to estimate changes in low flows during summer. In such periods river flow is fed by groundwater recharge, and ideally shows a gradual and stead decrease in flow are slow, until the onset of a new, major period of precipitation. The low flows simulated by the RHINEFLOW using the defined scenarios do not show a very pronounced change when compared to high flows. This response may be partly due to the definition of precipitation changes as percentages of present-day precipitation. Precipitation changes in dry summer will then be low, while the length of the dry periods remains unchanged. Also, transpiration rates by vegetation may alter if plants significantly adapt to the increased amounts of greenhouse gases.

Precise estimates of changes in peak flows demand a higher temporal resolution for the hydrological model than the 10-daily time step of RHINEFLOW. Nevertheless, using statistical downscaling techniques in combination with the RHINEFLOW output, estimates of changes in peak flows can be obtained.

14.2.2 The supply of sediment to the river Rhine drainage network

Modelling present-day sediment supply

The spatial database for the Rhine basin in combination with a simple model allowed identification of primary source areas, which, due to erosion by surface runoff, deliver sediment to stream channels. The average annual sediment supply amounts about 11.7 * 10^6 tons per year. Sediment supply is high during the end of spring due to high rainfall intensities on relatively bare soils. According to the RECODES model estimates, about half of all hillslope sediment production in the Rhine basin is presently delivered to stream channels. In spite of low erosion rates in forests, these cover large areas and so may quantitatively be as important as arable land as source area for the total sediment budget of the river Rhine. In most of the German and French sub-basins, the monthly variations in erosion and sediment supply are related to the dynamics of the agricultural system, to variations in rainfall erosivity and to the soil moisture state in the basin. Sediment supply resulting from erosion by snowmelt runoff plays a role in the higher parts of the basin and its sub-catchments.

Modelling sediment supply such as done in the present study for the entire Rhine basin is facing important scale problems. The model seems to over-estimate erosion on arable land and simulated sediment supply generally exceeds the observed sediment yields as in the river. Part of the uncertainty in the RECODES model predictions of sediment supply is due to errors in morphometric parameters, as these were derived from low spatial resolution data, which do not reflect the situation on the hillslope scale. The most important 'missing link' for the validation possibilities of RECODES is field data on hillslope sediment delivery ratios. Future research should focus on this issue. Since the morphometric parameters in the model are less sensitive to climate change, the estimated *relative* change in sediment supply due to climate change were expected to have less uncertainty.

Effects of environmental change

Both climate change and land use changes will affect erosion and sediment supply processes. In large parts of the Rhine basin, the projected climate change scenarios with increased winter rainfall and rainfall intensities will accelerate soil erosion and runoff. Erosion related to snowmelt will reduce. Since the land use change projections generally envisage a reduction in land use types that are susceptible to erosion, these will counterpart the effect of the increasing erosivity. Erosion and sediment supply will increase significantly in the Alps. Since this material is trapped in the many large lakes at the foot of the Alps in Switzerland, it is not available for transport to the Dutch waters. The amount of sediment that is mobilised by soil erosion and supplied to stream channels by overland flow, and which is potentially available for transport to the lower River Rhine, is likely to decrease slightly (with about 11%). This conclusion holds for the central estimate of climate change as employed in this report (UKHI 2050) together with the CPC land use scenario. The supply of sediment will increase in case land use does not change (i.e. remains similar to the land use in 1990) or if climate changes more than projected in the UKHI 2050 scenario.

14.2.3 Transport and deposition of fine suspended sediment in the River Rhine

Present climate and land use conditions

Under present climate and land use conditions, only about 27% of the 11.7 million tons of material supplied from hillslopes in the entire Rhine basin reaches the German-Dutch border. The remaining part is deposited. In the Alpine rivers most sediment is deposited in lakes, such as the Bodensee. In the German tributaries much sediment is stored behind obstacles in channels, such as weirs. However, most sediment entering the Mosel River reaches the outlet of this tributary. In the Rhine downstream of Andernach floodplain sedimentation is an important factor in the loss of sediment from transport.

The results of the sediment transport models were in agreement with the observed patterns of fine suspended sediment transport in the Rhine basin. However, several problems remained in the apparent over-estimation of sediment supply and sediment transport during specific months of the year, particularly at the end of spring - early summer.

Near the Dutch-German border, sediment transported is most effective when river discharge is between 2000 to 3000 m^3/s, close to average discharge. Extreme discharges (>6000 m^3/s) contribute little to the total annual suspended load in the lower River Rhine.

Floodplain sedimentation in the Netherlands takes place at discharges exceeding about 5000 m^3/s at Lobith. Estimated average annual sedimentation rates are in the order of 1.5 to 3 kg/m^2, and display a high spatial variability. Most sediment is deposited at moderately high river discharges during which the floodplains are just inundated.

Changed climate and land use conditions

Due to changes in climate-induced erosion rates, the total annual sediment load of the Rhine near Rees is expected to rise. Under the assumption that no changes in sediment delivery ratios occur, however, autonomous changes in land use will reduce the annual sediment load at the Dutch-German border by about 17%. Land use change in combination with climate change will reduce the annual load at Rees by about 13%. This mainly is caused by decreased sediment transport at discharges between 2000 and 7500 m^3/s. Sediment transport at very high discharge exceeding 7500 m^3/s is expected to increase. Due to this shift in transport, floodplain sedimentation in the Netherlands is expected to decrease by about 10 to 15%, depending on floodplain elevation. The uncertainty range in expected changes due to uncertainties in climate change estimates is large: -35% to +44% or more.

14.3 Implications for the Netherlands

Climate change can lead to important changes in the boundary conditions of the water systems in the Netherlands. At the upstream border the intra-annual variability in the influx of Rhine water will increase, with higher discharge peaks in winter and a reduction of flow in summer. At the downstream border a sea level may rise by several dm. Finally, direct climate parameters will change: winters will be warmer and wetter while water deficit will be larger during summer, although heavy rainfall events become more intensive. This demands a larger capacity of the regional water systems for storing and discharging water. In the lower estuary, a combination of low river flow and sea level rise will amplify the effects of partly reopening the Haringvliet barrier, as it will cause saline water intruding farther upstream into the estuary. Also, peak water levels are expected to rise here. Due to sea level rise the current target lake levels in the IJsselmeer will be exceeded most of the time in winter, while a reduction of inflow of Rhine water during summer will cause water levels falling below the current target level.

In addition to climate change and sea level rise, land subsidence and land use changes have been considered in the hydrological scenarios for the terrestrial areas in the Netherlands. Geographically, the ongoing subsidence and climate change will enhance the present-day differences between the higher Pleistocene areas in the SE part of the country where infiltration is enhanced and the low lying polder areas in the W part where upward seepage flows intensify. This results in a lowering of groundwater levels in infiltration areas and higher groundwater levels in seepage areas. The effect of sea level change can only be determined within the direct area of the North seashore and the lake IJsselmeer. Soil subsidence will demand an intensification of current water management measures in the polder areas, unless new strategies are adopted that do not envisage permanent drainage to reduce groundwater levels.

In the following section the implications for the water functions across the different water systems in the Netherlands are summarised.

14.4 Implications for functions

Safety

Together with increased winter discharges, the design discharge for safety standards along the Rhine will increase. Under conditions of the central estimate of climate change the increase may be in the order of 5% by the year 2050 and 10% by the year 2100. Statistical extrapolation of discharges suggest that under the extreme scenario for the year 2100 the design discharge might be as high as 20,000 m^3/s. Since safety against flooding is an uncompromising demand by society, the discharge and storage capacity of the river channels must be enlarged, allowing less physical space for other functions such as nature, agriculture or industry. If the design discharge would rise to such amounts as 16,500 m^3/s concurrent visions on landscaping of the floodplain may provide sufficient opportunities for compensating the rise of peak water levels. However, in case of the design discharge exceeding 16,500 or even 17,000 m^3/s, this would demand far reaching flood reduction measures within the high-water bed, including floodplain lowering over large areas. This would imply an increasing limitation of the implementation of the target ecotopes with river forests as defined by Postma et al. (1995), and culturally valuable floodplains would be affected over areas, while it will be hard to avoid implementation of local dike enforcement. Flood reduction measures in the upstream basin, including water retention and renaturalisation, will increasingly be needed to alleviate flood risk. Also, local widening the high-water bed of the rivers and appointing areas for water retention within the Netherlands must seriously be considered. In the extreme scenario of climate change with a presently unimaginable high design discharge of 20,000 m^3/s, even the currently foreseen retention measures may no longer be adequate in intercepting such large water flows. For such cases, a different order of strategies should be considered, such as recently suggested in the 'Rijn op Termijn' study of WLIDelft Hydraulics (1998).

In the lower estuary, the combined effect of sea level rise and increased peak flows of the Rhine may lead to an increase in the design water levels, particularly in the central and southern parts of the former estuary. The storm surge barriers will on average be closed more frequently. Widening the channels is expected to have little effect on flood water levels; on the contrary, it may cause the influence of storm surges from sea is marked farther upstream on the rivers.

Extreme water levels along the IJsselmeer lakes rise along with sea level. Wind set-up considerably influences extreme lake levels. However, the current climate scenarios do not provide any reliable insight in the changes in storm frequency, track and strength wind speed. Therefore, the estimates in the present study assume an unchanged wind regime. Higher lake levels will reduce the discharge possibilities of excess water from the surrounding polders in winter. Shallow foreshores along the lake's dikes may effectively reduce the impact of wave action on the banks. Also, increasing the discharge capacity of the Afsluitdijk sluices may efficiently counterbalance a minor rise of lake levels.

Inland navigation

Inland navigation will be mainly affected by changing water levels on the Rhine between Rotterdam and Basle. In case the navigation sector would not be able to adapt, the hydrological changes would gradually reduce the transport reliability, and increase transport costs by inland shipping by hundreds of millions DFL per year.

The inland navigation transport sector, however, has to a certain degree an internal flexibility to cope with the variations in water levels that occur under present-day conditions. The climate-induced hydrological changes will put an additional pressure on the current flexibility, and raises the need for adaptation. In view of the long time horizon of the expected changes, various measures may be found to mitigate the problems of low navigation depth on the Rhine. These can be technical, logistic or economic in nature. Measures may not necessarily be carried out only by the navigation sector. The river management sector may implement measures for improving channel depth. More rigorous measures would aim at retaining and storing water in the upstream parts of the Rhine basin, in order to achieve a larger base flow during dry periods in summer. Such measures will only be feasible when they are considered within the framework of integrated water management measures for the entire Rhine basin.

Climate change may thus affect the sector and raises the need for adaptation. When compared to economic and other developments, however, climate change contributes only moderately to the total uncertainty the inland navigation sector has to deal with in their future perspectives.

Agriculture

In the upstream parts of the Rhine basin, land use and land use changes strongly determine the amounts of sediment that can be produced by rainfall erosion. Scenarios for land use changes in the Rhine basin, which also affect agriculture, will be largely determined by EC-regulations and policy. The scenarios of Veeneklaas et al. (1994) have indicated that autonomous (driven by socio-economic and political forces) developments may reduce the area of land used for agriculture in the entire Rhine basin between 0 and 3 million hectares. With climate change, this area may further decrease by 0.2 million hectares. Depending on the socio-economic scenario, the area of land used for agriculture in the Netherlands may be decreased by nearly 7% (Projectgroep Watersysteemverkenningen, 1996). Within the high-water bed of the lower river Rhine branches, the consequences for agriculture are mostly determined by the landscaping vision adopted, and not by climate.

Nevertheless, climate change will affect those areas that are used for agriculture. During summer, the water deficit will increase due to enhanced evapotranspiration. At the same time, there will be less water available from the Rhine for agricultural use in the Netherlands. During dry summer periods, the water demand from the IJsselmeer for agricultural use may exceed the inflow of fresh water through the IJssel River, and the lake level may temporarily fall below the summer target level. Climate change enhances the rise of salinity in the Rhine-Meuse estuary, which results from alternative sluice management programmes of the Haringvliet barrier. This will drastically reduce the possibilities for freshwater intake for agriculture.

In a more direct way, wetter conditions will cause an increase of the water logging damage and a reduction of drought damage in the Netherlands. The potential damage, however, is spatially highly variable, due to the different local hydrological conditions. First estimates for the central estimate for 2050 indicate an increase of the total annual water logging damage for the Netherlands by the order of 50 millions DFL. The damage progressively increases if climate would further change. The largest damages are foreseen for the northern and eastern parts of the Netherlands. Because of increased salinity, the freshwater demand for flushing the polders will increase.

Increased atmospheric CO_2 concentrations and the direct temperature rise may affect assimilation efficiency, biomass production and length of the growing season of crops. Previous studies have indicated a positive effect on crop production (Roetter & Van Diepen, 1994). However, as these effects also depend on the introduction of new crop varieties or even different crop types, they fell beyond the scope of the present study.

The overall cost changes, when considered on a nation-wide scale, will largely depend on the adopted land use changes for socio-economic reasons. The effects for individual farmers may be different, depending on the local hydrological conditions, and the productiveness of different crop types. The sector might adapt to changing conditions by introducing crop varieties that are better resistant to extremely wet and dry conditions.

Ecology

Wet terrestrial ecosystems that depend on shallow groundwater tables will profit from intensified upward seepage in the lower regions. Moreover, due to a rise in groundwater tables, larger areas will be suitable for wet ecotopes. Wetter conditions, as predicted by the models for the Netherlands will reduce the desiccation problems in most nature conservation areas. However, the water deficit causing the 'background desiccation' is about 6 times larger than the estimated climate-induced rise of the groundwater level in nature conservation areas. In the coastal areas the intensified salt intrusion induced by sea level rise is expected to affect vegetation.

The lower river Rhine branches and their embanked floodplains are important parts of the main ecological network (EHS) in the Netherlands. The changes in the river Rhine regime will lead to more frequent flooding of the floodplain in winter and accelerated overbank sedimentation. This increase of floodplain dynamics is generally desired for ecological development, leading to larger areas of wet ecotopes and a more varied spatial arrangement of different vegetation types. Low flows during summer, however, result in low river water levels, which in turn leads to lower groundwater levels for wet floodplain ecotopes. Flood reduction measures within the floodplain will change the abiotic conditions of ecotopes. Lowering the floodplain will increase the areas of wet ecotopes at the cost of the present pastures, but also reduces the area of dry ecotopes. In case of a serious increase of the design discharge, the current target ecotope types of river forests as defined by Postma et al. (1995) can only be allowed at a few sites sheltered from the water flow. Instead, an alternative target of wet vegetation types should be considered. Ecological changes in the lower estuary will be dominated by the choice of future sluice management regime of the Haringvliet barrier. All these sluice management alternatives aim at ecological restoration; their effects will be amplified by climate change.

Higher winter levels and low summer levels in the IJsselmeer area are supposed beneficial for ecology. Both climate change and the REF2050 water management scenario are expected to lead to such conditions. The effects on the average residence time of the water in the lakes are small. The reduction in residence time in summer is advantageous for water quality. Climate change is not expected to influence chloride concentrations in the lakes, assuming an unchanged quality of incoming Rhine water. Higher water temperatures of the lakes, however, area may increase the risk of algae bloom. Shallow forelands may offer space for new habitats.

14.5 Policy implications and future Perspectives

The present study has demonstrated that the Netherlands is potentially vulnerable to changes in climate and sea level rise. This vulnerability will increase because the lower part of the country is continuously subsiding. Also, socio-economic factors contribute to increasing vulnerability. Larger claims by various water users, increasing agricultural production, growing population, changing lifestyles, economic expansion and investments in low-lying areas will increasingly become sensitive to extreme hydrological conditions. In view of the flood risk and the significance of sufficient fresh water, flood protection and the preservation of a sound water system, also in the long term, are of vital importance.

The appropriate management response to climate change here may include the following key-principles:

- No-regret policy;
  - 'win-win' strategies;
  - flexible towards the future;
  - robust planning.
- Planning for sustainability;
  - 'planning with water' instead of 'competing against water';
  - consider institutional and managerial measures instead of technical solutions;
- Planning for multiple objectives; and
- Integrated planning.

Long-term plans and designs should be flexible and adaptable to changing insights on climate impacts. The design of such structures should anticipate possible effects of climate change that may become manifest after the forthcoming decades. Anticipatory measures combining the primary aims of the measures with other objectives should be undertaken in combination with on-going activities An example is the spatial 'reservation' of sufficiently large floodplain areas alongside the rivers in combination with ecological rehabilitation. Adaptive measures and strategies, which aim at making sectors more resilient to today's conditions are at the same time beneficial in adjusting to future changes in climate. Such measures and strategies – the 'win-win' measures – could have multiple benefits and most likely would prove to be beneficial even in the absence of climate change. Measures and strategies should be flexible, allowing adaptation along with changing insights on climate change and changing demands from the user functions.

An implementation of these principles is the policy of 'making way for the rivers' adopted in 1996 by the Ministry of Transport, Public Works and Water Management and the Ministry of Housing, Spatial Planning and the Environment supplementing the national Flood Protection Act. The policy has two key objectives: improving flood defence systems and controlling the impact of any flooding that would nevertheless occur. In principle, therefore, only river-bound activities such as shipyards, which need to be sited on the rivers, will be allowed into riverside locations. Activities which have no direct ties with the rivers - recreation parks, for example - will not be approved unless there is special need. Spatial reservations along the riverside should be made already now to allow widening the channel when needed in future. Meanwhile, these areas can be used for nature and ecological rehabilitation along the Rhine.

Planning should be robust: measures and infrastructure should be designed such that they are effective or functional also in case future conditions are different from what is presently foreseen. Otherwise, such measures might need very expensive adaptation to ensure their functioning under changing conditions. Or, even worse, these measures might prove to be very expensive solutions for problems that no longer exist.

14.6 Future research

Based on these observations, it is clear that the question is not whether we should define policies for dealing with the uncertain future. It is much more important, despite the inherent uncertainties, to focus on the question of how societies can develop mitigating strategies and how societies can adapt to climate change. Scenarios can be helpful tools in developing, analysing and evaluating future strategies. However, many different scenarios already exist in the above fields of economy, demography, lifestyle, agriculture, physical environment and climate change. All these scenarios differ in terms of underlying assumptions and perspectives. Depending on the perspectives of the future, different water management strategies may be adopted. The question that rises is then: which is, given the uncertain future, the best water management strategy? Therefore, in addition to research into the reduction of uncertainties in the modelling of climate and hydrological responses, methods are required to structure and inter-relate various categories of future developments into integrated and consistent sets of scenarios that can be used for integrated assessment studies in the Rhine basin.

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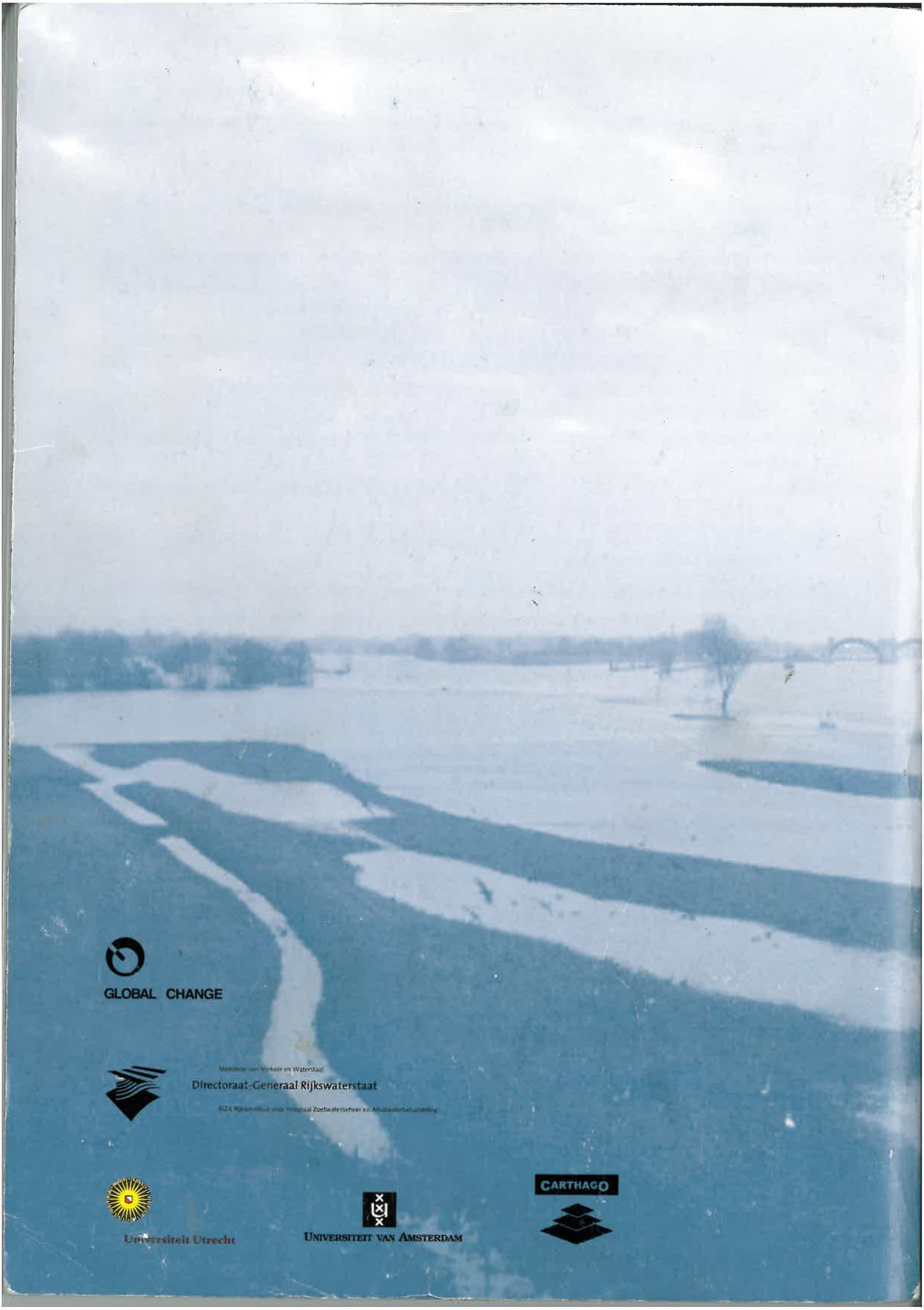

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